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The Tundra Environment

A Symposium of Section III of the
Royal Society of Canada

Winnipeg, 3 June 1970

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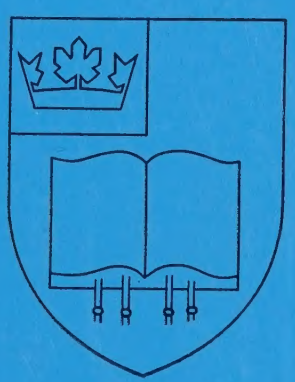

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The Tundra Environment

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of the Royal Society of Canada
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Foreword

On 3 June 1970, at its meeting in Winnipeg, Section III of the Royal Society of Canada held a symposium on the tundra environment. Papers were read by four specialists on the area, one of whom came from the oil industry and the others from the universities. There was formal discussion from the platform, followed by far-ranging comment from the floor. At the end of the symposium a motion was put (by the president of Section III) and carried. This was later adopted by the Council of the Society itself in the following form:

RESOLVED: – that the Royal Society of Canada shares the concern for the future of the tundra environment expressed by all the speakers at the Symposium held in Winnipeg on June 3rd, 1970;
– that the proceedings of the Symposium, including both papers of the panellists and the remarks of the principal discussers, be published as early as possible;
– that the principle that there should be adopted and enforced stiff regulations for environmental conservation in the North be strongly supported;
– that the Society be urged to give the widest possible immediate publicity to these findings.

This short publication fulfills the Council's instructions. The panellists included myself, L. C. Bliss, W. O. Pruitt, Jr., and R. A. Hemstock. J. D. Ives and G. A. McKay were the formal discussants. No distinction has been made between these papers, however, since all were addressed to the same subject and are of equal weight. They are presented in the order in which they were read.

Most of us were on unfamiliar ground, since we were trying to influence

public opinion rather than doing the more familiar job of exposing our scientific work to the criticism of our fellows. Scientists are uneasy propagandists. But we are at a moment of our national history when it is still possible for us to act towards nature as we have rarely acted before – wisely, humanely, and with an eye towards the future. At such a moment only the irresponsible stay away from public controversy.

F. KENNETH HARE
Chairman of the Symposium

L. C. BLISS*

Oil and the Ecology of the Arctic†

Most people have heard of the discovery of oil at Prudhoe Bay, Alaska, in 1968 and at Atkinson Point, N.W.T., in early 1970, and of the two voyages of the ice-breaker tanker *Manhattan*. Associated with these oil discoveries and that of natural gas in the arctic islands, there has been a great concern for ecology in the arctic. It is commonly stated that the arctic environment is fragile and must be protected, yet there has been difficulty in translating this into a meaningful modus operandi. We find that the arctic, those lands north of the tree-line, is of interest and concern to many and that the subject of exploration for and future harvesting of oil and base metals is an emotionally explosive topic in terms of economics, politics, and ecology. The purpose of this paper is to discuss the ecological problems presented by large-scale arctic operations and the means of lessening the impact of these operations so as to maintain a favourable arctic environment for future generations.

THE ARCTIC AS A FRAGILE ECOSYSTEM

Ecologically, the arctic is considered to be fragile for several reasons. In the arctic as in other severe environments, there is a reduction in the number of plant and animal species that function within the ecological systems (ecosystems). Although there may be large populations within a particular species such as the lemming, caribou, and various species of sedge and willow, it is difficult to predict what will happen if a key species is eliminated, for there are few other species that can fill the same ecological

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†An address delivered to a symposium on "The Tundra Environment."

niche or position. Thus the loss or severe reduction of arctic species is potentially more serious than similar losses in temperate or tropical regions where there are more species.

Secondly, species grow slowly in the arctic, so that if plants are killed by surface disturbance or if fish, caribou, or fox are greatly reduced in numbers, it takes longer for the populations to reach their former levels. The destruction of vegetation by surface disturbance is an especially serious problem, for it results in a reduction in the numbers of large mammals such as muskox and polar bear.

A final major reason for considering these as fragile ecosystems is that in regions with a high ice content in the permafrost and with a rather complete cover of plants, loss of plant cover usually leads to excessive ground thaw. With the melting of the ice, there is a heat-induced surface subsidence that results in a special kind of erosion called thermokarst. This occurs because the thawing of the permafrost takes place more rapidly than plant growth until a new equilibrium level is reached. Thermokarst development is not important in coarse-textured materials such as sands and gravels, but it is potentially important in peats, silts, and clays where the ice content may be 50 to 70 per cent by volume and up to 100 per cent in ice wedges.

Thermokarst is well documented for the low arctic as on the mainland of the Northwest Territories, Yukon, and Alaska, but is less well known in the central and northern islands of the Arctic Archipelago or the high arctic. In these latter areas there is much less plant cover, and the removal of what few plants there are may have a lesser effect on changing the surface albedo and heat budget. We are initiating studies on these problems in both the low and high arctic this summer.

PROBLEMS OF SURFACE DISTURBANCE

Many of the environmentally induced problems associated with mineral exploration and production in the arctic are related to permafrost. Permafrost problems are not new to those federal agencies and industries that have worked in the arctic and sub-arctic for a number of years; to many of the big companies that have not worked there until recently, however, permafrost presents an entirely new set of problems. People in industry and federal agencies have often gone to the arctic as to the tropics with the preconceived notion that technology developed in temperate regions will work in other environments, but in many cases this has only led to severe problems and high development costs.

To illustrate, let me use as an example the Trans Alaskan Pipeline System (TAPS) and the concept of construction as presented at a meeting in June 1969 in Fairbanks. It was recognized that the 4-foot-diameter

pipe should be elevated 8 to 10 feet in areas of permafrost with high ice content, an estimated distance of 40 miles. However, current estimates, based on the actual extent of permafrost with a high ice content, call for at least 150 to 200 miles of elevated pipe. The pictures displayed at the meeting showed a caterpillar-drawn pipe-installing machine with side-loading booms as used in temperate regions. Such a machine would become buried in mud in many areas of the arctic if used in the summer, but no summer restriction was mentioned by the scheme's proponents. Indeed, even in winter, the area adjacent to the pipeline would be churned at the surface if track vehicles were used. A drastic change in machinery for laying pipelines is needed for areas of permafrost so that little disturbance to the tundra surface occurs. Other pictures showed drill sites built on a gravel pad with little surrounding disturbance and, for comparison, other wells where the surrounding wet land tundra was all churned up because no gravel pad was used and track vehicles were used in summer. The cost of terrain repair, once developmental and operational regulations are established, will be considerable to those companies that have not used proper precautions. A huge source of gravel becomes a critical requirement for drill pad construction as well as for roads; yet gravels are not plentiful and the removal of large areas of river gravels can change or destroy fish spawning beds as well as inducing other river changes.

Thermal problems related to permafrost can be greatly reduced with proper planning. The utilidors at Inuvik that carry steam, water, and sewage lines to houses and shops are elevated about four feet above the ground. These insulated units keep the heat from the frozen ground, and the heat release is sufficient to keep the water lines from freezing. All buildings there and at the Atlantic Richfield Company (ARCO) complex at Prudhoe Bay are elevated three to six feet above the ground, again to isolate the heat load of buildings from the permafrost. Much of this engineering design has resulted from the research of the National Research Council's Division of Building Research and the Cold Regions Research and Engineering Laboratory of the United States Army.

Road construction has also been modified so that gravels are tail-gated over the tundra vegetation from the existing road in order to use the buried vegetation as an insulating layer. Mr Trueman, the engineer in charge of the Dempster Highway construction, has followed this practice for several years. This contrasts markedly with the practice followed in temperate regions where all vegetation is first bulldozed away. Road thickness depends upon the load capacity of the substrate and the weight of vehicles. The Dempster Highway running north from Dawson City has a gravel bed of one to two feet over rather heavy clay soils with relatively little peat, but the roads in the Prudhoe Bay area with its deep peats and heavy truck loads are five to six feet thick.

The oil industry is recognizing its mistakes of the 1967–8 Alaskan oil rush and similar mistakes in the Mackenzie Delta. Imperial Oil and other companies have restricted the overland movement of heavy vehicles, including seismic crews, to the freeze-up periods of the year. In the remainder of the year, helicopters, vehicles with low-pressure balloon tires, and hovercraft are being used and further developed to reduce the surface disturbance factor. These practices have been introduced without government regulation, a very significant point. The journal *Oilweek* is full of articles on the development of vehicles for tundra use.

The oil industry has recognized the need for disturbance studies including surface rehabilitation research. Imperial Oil, largely through the efforts of Mr R. A. Hemstock, initiated rehabilitation studies at Inuvik and Tuktoyaktuk in 1968–9 before ecologists became interested in such research. From their initial work an expanded program in both the low arctic of the Mackenzie Delta and the Alaskan Coastal Plain and the high arctic of Devon Island is being launched this year. Areas of past surface disturbance will be studied to determine what kinds of substrate and vegetation are most susceptible to damage and to learn what plants reinvade such disturbed sites. Other studies will be conducted to determine the kinds of plants and mulches that should be used to speed the rehabilitation of such surfaces in order to reduce, where possible, the development of thermokarst. The word models shown in Figures 1 and 2 depict the dynamics of untreated and treated surface disturbances.

The fragility of tundra vegetation and the role of an increased summer thaw are illustrated by the activities of man and dog on Garry Island in the Mackenzie Delta. Dr Ross Mackay and his students from the University of British Columbia used a walking-trail for three summers with the result that a gully about one foot deep developed at its upper end and over five feet deep at its lower end near the shore. Cotton-grass plants flower and fruit much more abundantly along this "trail." A dog was tied at a stake for 10 days and the vegetation became disturbed sufficiently to cause the surface to subside over one foot. Our own research on plant production and surface disturbance has shown that cotton-grass tussocks become brown and matted after they have been walked over a few times. Such effects may lead to accelerated summer thaw. On cat tracks made on winter roads many dead heath shrubs and mosses are seen in summer, yet the cotton-grass tussocks show accelerated growth and flowering. Research on these interesting problems is now under way.

To date the emphasis has been on the estimated 10 to 30 billion barrels of oil in the Prudhoe Bay fields, but natural gas is also present in great quantities. The estimates of this associated gas run to at least five trillion cubic feet. Much of this gas will be harvested and shipped south for urban and industrial use, but some of it will also be flared in the arctic. Such burning of gas and oil will produce at least some level of air pollution and

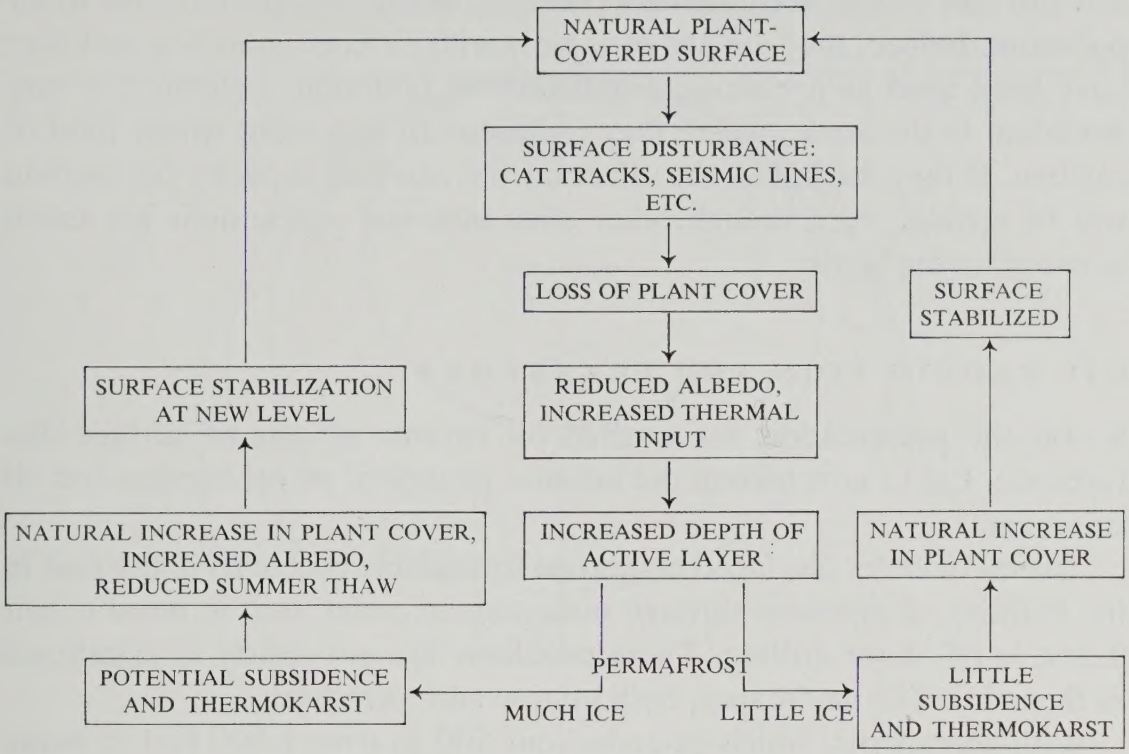

FIGURE 1. Plant surface manipulation word model (natural sequence).

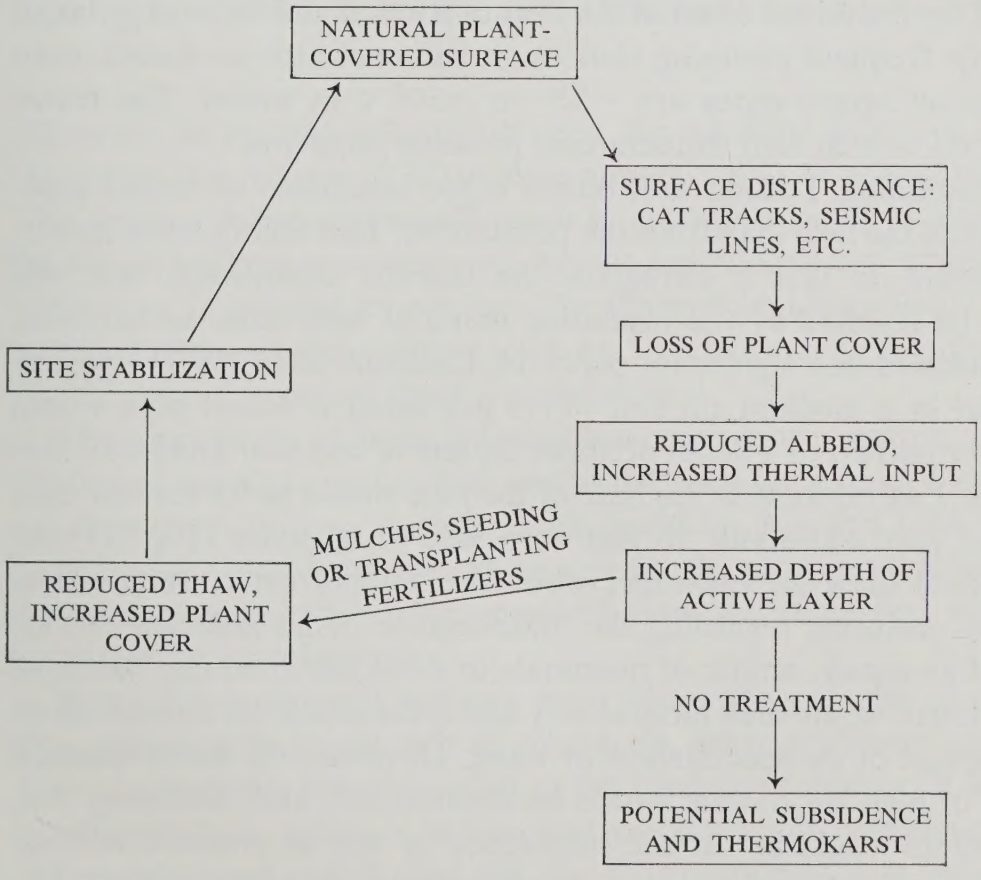

FIGURE 2. Plant surface manipulation word model (rehabilitation sequence).

this can and will be detrimental to lichens, which are very sensitive to air pollution. Indeed, they die out so rapidly with air contamination that they have been used as a biological indicator of pollution. Lichens are very abundant in the arctic, where they represent an important winter food of caribou. If they are killed, the effect on the carrying capacity for caribou will be serious, even though other environmental precautions are taken to maintain the herds.

OIL PRODUCTION AND TRANSPORT

So far the presentation has centred on various aspects of surface disturbance. Let us now turn to the broader picture of oil production and oil shipment.

The oil industry has faced numerous formidable problems in the past in the building of pipelines through mountainous areas and, in more recent years, in off-shore drilling. These problems are not nearly as significant as those in arctic landscapes, both marine and terrestrial.

With permafrost, which extends from 500 to over 1,500 feet in many areas, well casings must be specially anchored. Oil at the well-head generally has a temperature of 65° to 80° C, and casing supports can therefore rapidly be melted away, resulting in blown casings and a gusher. The oil to be piped may enter the line at the well-head temperature, and because of the combined effect of the heat of friction and the energy introduced at the frequent pumping stations, it will cool little in transit, even though the air temperatures are −35° to −50° C in winter. The transmission of oil at such high temperatures presents problems.

In the beginning, I along with others urged insulation of buried pipelines to isolate the heat load from the permafrost. This theory has a serious fault, however, in that it disregards the thermal equilibrium that will inevitably be reached by the insulating material with time, as has been well documented in a significant paper by Lachenbruch (1970). He calculates that in a medium silt soil (17.5 per cent) a 4-foot pipe would thaw the permafrost to a depth of about 26 feet in one year and to 49 feet in 20 years. Lateral thaw at the base of the pipe would be 15 feet on each side in one year and about 30 feet on a side in 20 years (Fig. 3); the surface lateral thaw in September would be much greater. Such effects raise many problems regarding the maintenance of an adjacent service road, pipeline repair, ability of mammals to cross the area, etc. Areas of high ice content would melt more slowly and areas of low ice content more rapidly because of the specific heat of water. However, the water released from soils of high ice content would be considerable and, following evaporation, there would be surface subsidence as well as potential surface erosion on slopes during melt-out. Should the surrounding material become liquefied the pipe would either sink or float depending upon the

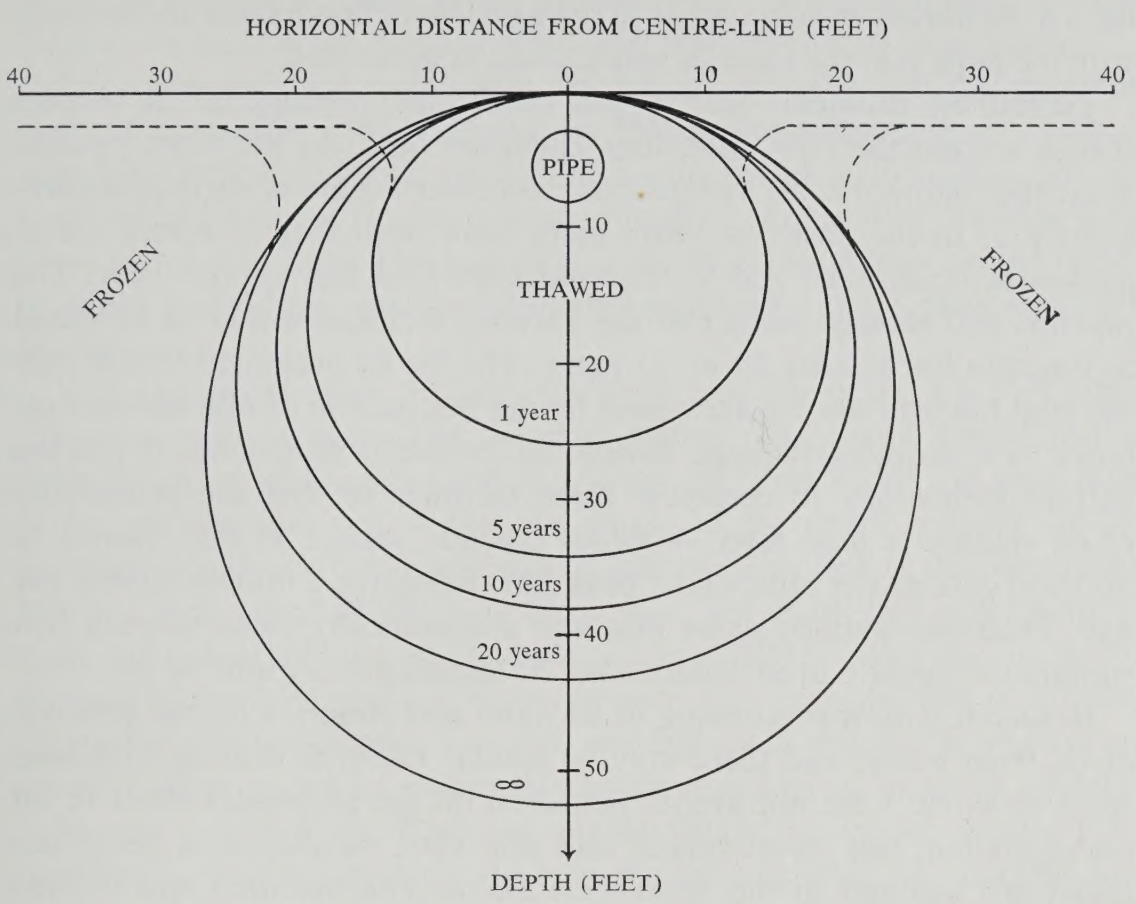

FIGURE 3. Growth of the thawed cylinder around a 4-foot-diameter pipe with its axis 8 feet beneath the surface and its temperature maintained at 80° C.

difference in specific gravity between the oil-filled pipe (ca. 1.2) and the soil (1.0 in organic to 2.0 in some mineral soils) (Lachenbruch 1970). The stresses introduced would result in inevitable ruptures unless a careful weight balance were achieved, but the weighing factor would vary with differences in soil and ice content. The thermal problems would be greatly lessened if the oil were cooled to about 5° C before entering the pipeline, but the cost of a cooling plant is prohibitive.

These problems point to the need for much more analysis and experimentation prior to construction and to the need for a careful examination of alternative designs. A large ditch could be dug and back-filled with gravel, which would provide a heat sink for the pipe, but this would result in large piles of overburden removed from the ditch and would again require huge gravel supplies.

If the line is elevated in those areas where the soils are of medium or fine texture, with burial only in river-beds, other problems arise, though they are probably less damaging to the total environment. It is not clear whether caribou, reindeer, moose, and muskox would consider an elevated line as a fence or not. If they did, the construction of lines would have to be planned so that they did not block migration routes and the lines would

have to be buried where possible in river gravels of floodplains and terraces with the hope that the animals would cross at these sites.

Permafrost problems and rugged mountain crossings in the Alaska Range are not the only difficulties engineers face. As the TAPS pipeline nears the southern coast at Valdez, it will enter a zone of earthquake frequency 3. In the past few years there have been several severe earthquakes at Anchorage and Valdez and numerous less intense ones. The pipeline and storage tanks and the harbour facilities would be expected to function for at least 20 to 30 years. The threat presented to not only the land but also the coastal waters by the destruction of line and storage tanks by a major earthquake during that period is very great. It will tax current technology to construct these facilities so that the probability of oil spillage is near zero. A 4-foot pipeline carries 11,000 barrels or 500,000 gallons per mile, and a peak flow will carry 2 million barrels per day. Pressure-operated gates that will automatically close when a line rupture or pressure drop occurs must be installed every mile or so.

Research is now proceeding in England and America on the removal of oil from water, and there may be similar research dealing with land spills of which I am not aware. Research on the ecological effect of oil on vegetation, soil invertebrates, and soil water movement is being initiated this summer in the Mackenzie Delta. This research will include studies of the rates of natural oil decomposition and methods of speeding these rates. Much of the associated laboratory research will be done at the University of Calgary. The industry is supporting this work for it is sincere in wanting to lessen the environmental impact of oil spills and it realizes that the only way to do this is to study the problems before they occur.

A second proposed line, the Mackenzie Valley Pipeline, would bring oil from Alaska and the Canadian arctic through Edmonton to markets in eastern Canada and the central United States. This line, though greater in length and more costly than the TAPS line, would deliver the oil to the markets that need it. Oil shipped by tanker from Valdez to Seattle or San Francisco would place 2 million barrels per day in an area with a projected deficit of only 500,000 barrels per day, and would necessitate the construction of a second costly line from the West to the Midwest.

The third method of oil transport is via ice-breaker supertankers or, in the more distant future, via submarine tankers. The first voyage of the *Manhattan* was very successful according to the public relations communiqués. The ship sailed north and west until it reached the ice ridges of McClure Strait, which forced her south via the Prince of Wales Strait to Prudhoe Bay. She sailed at the most ice-free time of year, and in the best summer in about 50 years. In addition she had an ice-breaker escort plus helicopters for surveillance. The ship returned to the east coast with

two huge holes in her hull, hardly indicative of a safe first voyage, though these holes were in the portion of the hull without special reinforcing.

The spring trip was hailed with much fanfare, yet once the *Manhattan* reached heavy ice-fields and pressure ridges, the communiqués became very few. It is difficult to assess single voyages of such a ship, for an economical system of transport would require a ship passing any one area every two to four days. This rate of passage would help keep a route open, provided it could be opened initially and provided severe storms were not too frequent.

With the loss of about 100 tankers in the past five years, it is inevitable that some tankers would sink in arctic waters. The costly lessons of the *Torrey Canyon* off England and the *Arrow* off Nova Scotia are indicative of the problem but not of the magnitude of the environmental consequences should a ship with millions of gallons of oil sink in the Northwest Passage. The effect of oil on seals, walrus, sea lions, and polar bear is grim, but potentially not as dramatic as the possible loss of marine algae, the base of the food chain in marine waters. The incorporation of oil into the pack-ice would increase the thaw and this could give rise to more open water in summer, with considerable resulting influence on arctic climate.

Should sizable fields of oil and gas be discovered in the Archipelago, removal by ship is probably the only feasible method. The current oil-fields on the mainland can be tapped for tanker shipment provided a port can be built on Herschel Island or a loading dock at Prudhoe Bay, probably 10 to 20 miles off-shore, because of the shallow waters and the deep draughts of the supertankers. Many technological and environmental problems must be solved, however, before such a port can be constructed.

I personally favour the Mackenzie Valley Pipeline route because it would get the oil to where it is needed and because the potential environmental dangers are somewhat less than for the TAPS pipeline and tanker routes. A major problem of the Mackenzie line is that if it serves the Prudhoe Bay fields, the line will have either to cross the Arctic Wildlife Range or to run to the south of the Brooks Range and east to the Mackenzie. The United States Department of Interior, Bureau of Sport Fisheries and Wildlife would certainly put up a stiff battle, as would conservation groups, to prevent a line crossing the Wildlife Range.

A very important point advocated by Mr Hemstock of Imperial Oil and others is that whatever line is built, it must serve as a corridor with all oil and gas lines, power lines, and roads running parallel, the temperate region concept of criss-crossing lines being discarded. A second important need is to restrict the gathering of seismic data by competing companies by setting up an exchange of information acquired in order to limit the running of lines, which are currently two miles or so apart. Environmental quality should have a higher priority than the accumulation of secret and

often unusable seismic data. It is recognized that this would be a significant change in corporate practice, yet the question should be put forth.

A new geotechnical research committee on pipeline and land use technology in northern terrain has been set up by the National Research Council. The committee will examine geotechnical problems that may arise from the construction of pipelines and related surface structures in the north. The formation of such a group, charged with coordinating and stimulating research on these problems, is a major step forward.

COST OF EXPLORATION, DEVELOPMENT, AND SHIPPING

As a final topic, let me consider the cost of exploration, oilfield development, and shipment, which is very high in the arctic. Land leases in Alaska have brought $900 million into the state treasury. This is fine for Alaska, but it will add significantly to the costs of these hydrocarbons when they reach market. Seismic lines cost $3,000 to $4,000 per mile over land and $500 per mile by boat over water. Oil wells cost several millions to drill and a goodly sum to operate. The TAPS line, if built, will cost about $1.2 billion. Such monies come from the profits of companies, the borrowing of funds, and the investments of stockholders who have gambled that future profits will justify the expenditure. While all stocks have dropped significantly on the New York Stock Exchange since their 1968 highs, Atlantic Richfield dropped from a high of $136 to about $45 per share and Standard Oil of New Jersey from $85 to $50 per share. Investor confidence ran rampant after the Prudhoe discovery and ARCO became a glamour stock; but a general lack of market confidence plus the financial risks of this company have reduced its price by over 60 per cent. (These data are not used to cast doubt on the financial status of sound companies, I should point out, but to illustrate the financial burden of northern oil development.)

Exploration and development expenditures produce economic and political pressure to harvest oil resources as soon as possible, to repay the staggering debts. Thus the consortium of companies in TAPS has stockpiled pipe at Valdez and will stockpile more pipe at Prudhoe Bay this summer with the purpose of pressuring the release of construction contracts from the Department of the Interior. Two court injunctions have been placed against the service road and pipeline until the environmental problems and demands of the native people have been met. These will delay construction at least a year. One can only hope that the land use regulations being developed by the Department of Indian Affairs and Northern Development will have sufficiently strong standards and enforcement procedures to maintain environmental quality in our arctic.

In this connection, I might mention, too, that as the number of people

and their mobility increase in the north, there is a direct threat to large mammals through poaching. Dr Pruitt will have much more to say on this topic. Let me only say that it must be the responsibility of government and industry to ensure the maintenance of viable herds of muskox, caribou, polar bear, marine animals, and waterfowl that are so important to the ecology and the native people of the north.

The competition of transportation routes is well illustrated by the estimates of getting the oil to market. In the 1 December 1969 issue of *Oilweek* the estimates are $1.10 per barrel via tanker; $1.00 via the TAPS line, tanker to Seattle, and pipeline to Chicago; and $0.55 via the Mackenzie Valley line to Chicago. However, Mr Richard Venn, vice-president and director of Humble Oil's marine department, has recently been quoted as saying that tankers are more economical. It is interesting to note that Standard Oil of New Jersey is involved in all three transportation projects. It is probably safe to say that all three estimates are low in relation to the final costs several years from now when one or all routes are completed.

The great pressure to get the arctic slope oil to market by 1972–3 will ease the financial burden on the industry but will add oil to an already oil-glutted nation and world market. The estimated doubling of oil consumption from 9 billion barrels in 1969 to 18 billion by 1980 in the United States will only add to the environmental problems of too many vehicles on the road and too much air pollution in our major cities. The ever increasing use of our hydrocarbons for energy rather than for plastics, drugs, and food should not continue. Future generations will condemn us for our wastefulness of these energy reserves.

These comments should not be interpreted to say that I am opposed to harvesting our hydrocarbon resources in the north for I am not. Rather, I am for a more sane pace and cost of such harvesting, one that will ensure their use for several future generations.

THE FUTURE

The future in the arctic is not one of gloom and doom, for governments and companies know that environmental quality holds a high priority in the minds of many people. There are several very encouraging indicators of cooperation of the federal government, industry, and the universities in the solution of arctic environmental problems. The new National Research Council committee on pipeline and land use technology has been mentioned above. Indian Affairs and Northern Development, the major oil companies in the Mackenzie Delta (Arctic Petroleum Operators Association), and people from universities across the country will initiate studies this summer on the effect of land surface and water disturbances on animals and plants, under the title Arctic Land Use Research. The objectives are to lessen the impact of environmental disturbances caused by

seismic lines, cat tracks, drill sites, and camps, and the influence of these activities on fur-bearing animals, waterfowl, and fish. Through these studies better predictions of the economic impact of a smaller population of fur-bearing animals, fish, and whale on the coastal native people, the impact of surface disturbance on plants and animals, and the cost of environmental repair should be possible.

A second study on Devon Island in the high arctic has the financial support of the Arctic Institute of North America, the Department of Indian Affairs and Northern Development, the Department of Energy, Mines and Resources, the National Research Council, at least five oil companies, and five universities. This project is to study the functioning of a natural ecological system and then to investigate portions of the system which have been stressed by oil spillage, track and seismic lines, road construction, etc. to determine the influence of the stress and the amount of stress the system can tolerate while still continuing to function. Much of the applied research will be conducted in the other islands where oil and gas exploration is active. Such studies will aid in the development of land use practices as well as land use regulations.

Thus, although the ecological problems are very great in our north, there are signs of cooperation from agencies and groups of people that can and must solve environmental problems on an interdisciplinary basis, for the problems are too complex to be solved by a few people or by competitive agencies. What is needed is a new breed of environmental scientist who will cut across the traditional lines of the engineering, biological, and physical sciences to solve environmental problems before deterioration reaches levels comparable to those of some of our more temperate regions. The hiring of ecologists by governments and industry will help them solve environmental problems as the hiring of engineers has solved many technological problems.

Agencies must realize that the cost of controlling environmental problems is much less if ecological indices are plugged into the initial construction and operation design just as engineering indices are now. In temperate regions we seldom considered ecological indices until very recently. We have a chance in the arctic to affect the decisions which are made by applying ecological theory and practice initially. When top officials in industry say they want answers on the effect of seismic blasts on seals out on the ice pack, on the ecological effect of oil spilled on land and water, and on the influence of roads on wildlife and vegetation, there is real hope. There is time, but we must act now.

REFERENCE

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WILLIAM O. PRUITT, JR.*

Tundra Animals: What Is Their Future?†

Eleven species of tundra animals (8 mammals and 3 birds) are listed by the International Union for the Conservation of Nature (IUCN) as "threatened" throughout their world range, and there is concern by IUCN for the survival of 21 additional species (8 mammals and 13 birds) (Holloway 1969). This is a higher percentage than in any other major biome in the world.

It is important to any discussion of tundra animals to have a clear concept of "tundra" and other related terms. The basic idea of tundra is a lack of trees, a definition that necessitates a definition of "tree." A tree, for our purposes, is a perennial woody plant no less than 2 metres high with a single central stem. Tundra was originally a Finnish word referring to the treeless plateau in northern Finland. This plateau is dissected by steep-walled, forested valleys. Farther south the proportion of forested land increases so that the "tunturi" are isolated, treeless domes. From its original meaning, the word tundra was carried into Russian to signify the treeless zone in northern Eurasia. Later it also came to designate the analogous zone in northern North America that some unthinking people still mistakenly call the "barren grounds."

We see how in protected valleys the forest can penetrate the tundra. As one proceeds in the tundra south, southwest, or sometimes even west, one encounters more shrubs, shrubby trees, and trees. Finally, groves of forest appear on the protected sides of hills and the shrubs, particularly dwarf birch, may blanket the landscape. Sometimes the trees are not in discrete groves but are thinly scattered, each tree at least a trunk length from its neighbour.

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†An address delivered to a symposium on "The Tundra Environment."

At some later point in our journey, we note that the trees are close enough for their branches to intermingle, or close enough for a red squirrel or a marten to move from tree to tree without coming to the ground.

Between the indefinite line where the trees and shrubs break the expanse of open tundra and another indefinite line where red squirrels have an arboreal highway lies the "forest-tundra." In North America we tend to look on this region as simply an ecotone between treed and treeless conditions. In Eurasia, however, because of its greater extent and also because of its greater role in human ecology, the forest-tundra is looked upon as a separate ecological entity.

Continuing our journey we enter the boreal forest, one of the most important (but least known) of the world's biomes. The circumboreal coniferous forest is properly known by the term "taiga" (Hoffman 1958). This is a well-established name for this biotic association, with roots reaching deep into Russian history and folklore. At one time some North American botanists attempted, mistakenly, to transfer the term to the forest-tundra, but thankfully the attempt has been unsuccessful.

While we are refining terms we should consider, for clarity's sake, "arctic," "subarctic," "high arctic," and "low arctic." And let us restrict our definitions to biology, ignoring climatologists', geophysicists', or geopoliticians' specialized definitions.

To North American biologists "arctic" means the region beyond tree-line and is thus synonymous with "tundra." Concurrently, "subarctic" means a region bounded by tree-line on one side and some other complex of criteria on the other. Sometimes this outer boundary is related to permafrost, sometimes to vegetation; it is unsettled in the literature.

In New World usage the "arctic" is divided into two subzones, "low" and "high." The low arctic is the tundra region where shrubs grow, where there is much snowfall, high winds, many storms, and where there may be rain or even thaw during the winter. The high arctic is the region of no shrubs, significant amount of unvegetated ground surface, reduced snowfall, fewer storms, and never any winter rain or thaw.

We should note, however, that in Eurasian usage our North American names are shifted northward. Thus our "low arctic tundra" would be referred to as "subarctic," and the term "arctic" in Soviet biological literature refers to what is called "high arctic" in North America. I suspect that much of our misunderstanding of the significance of Russian northern research stems from this confusion of terms.

I have spent such an inordinate amount of time clarifying non-tundra terms because, upon detailed study, we note that there are very few true tundra animals, even in the broadest sense. Many of those species commonly regarded as tundra animals actually depend on the forest-tundra or on the taiga to sustain their populations on a year-round basis.

Thus, in discussing tundra animals we must also consider the ecology of regions sometimes far distant from even low arctic tundra (North American usage).

In the remainder of this paper, great numbers of kinds of tundra animals will, perforce, remain unnoted. We know virtually nothing of the survival requirements of almost all the terrestrial invertebrates. We shall also ignore the fishes and invertebrates of tundra ponds and streams. In order to emphasize the extent of our knowledge I have limited examples and references almost entirely to North American and Greenland sources. One should, of course, recognize the vast amount of research that has been done in the Eurasian tundra and the extremely rich literature that has resulted.

The remaining tundra animals, the birds and mammals, can be divided into two groups, permanent residents and migrators. There are very few permanent residents among the birds: ravens, willow ptarmigans, rock ptarmigans, snowy owls are about all that can be counted on regularly in the inland tundra at all seasons. Among the mammals, the permanent residents over most of the inland tundra are one or two species of shrews, coloured fox, white fox, wolf, barren-ground grizzly, weasel, wolverine, usually four species of microtine rodents (*Microtus, Clethrionomys, Lemmus*, and *Dicrostonyx*), ground squirrel, muskox, and a few caribou. In certain mountain regions we should add the hoary marmot. The grizzly, ground squirrel, and marmot are inactive in winter.

When the migratory animals return to the tundra in summer there is a dramatic change in the biotic community. There are four main types of migratory birds that nest on the tundra or associated areas: the insectivorous birds, the waterfowl, the carnivorous birds, and the cliff-nesting species. Among the mammals the most important migrator is the caribou.

Every species, including man, has certain minimum habitat requirements. For most tundra species the survival requirements may be categorized as (1) breeding range, (2) summer range, (3) winter range. We should add, perhaps, another category of some specialized survival requirements. On this basis, then, we can survey most of the tundra animals (see Table 1).

One may analyse this outline of range requirements from two points of view, namely, simple occurrence and relative importance of the species in the tundra ecosystem. On the basis of the number of species involved:

1. There are three important types of breeding range: (a) rocky or cliffy regions with talus; (b) rocky or tussocky uplands, including rolling uplands with birch-heath-cottonsedge tussocks; (c) sandy eskers.
2. There are two important types of summer range: (a) rocky or tussocky upland, including rolling uplands with birch-heath-cottonsedge tussocks; (b) lowlands, stream and lake edges.

TABLE I

Species	Breeding range	Summer range	Winter range	Other
Permanent residents				
Raven (Snyder 1957)	Rocky, cliffy country	Wide variety of food sources, vegetable and animal	Stable food source	Highly adaptable sp.; will probably survive in north longer than technological man
Ptarmigan, willow and rock (Snyder 1957)	Upland, rocky or tussocky areas	Birch-heath-cottonsedge tussocks	Varied topography, so that vyduvs and zabois interdigitate with dwarf birch and heaths	Will survive in close proximity of human habitation if protected from shooting, disturbance, and stray pets
Snowy owl (Snyder 1957)	Good microtine pops; scattered hummocks or mounds for nest sites	Same as breeding range		Heavily dependent on state of microtine cycle; other factors insignificant in face of this one
Shrews (Pruitt 1966b)	Too little known to make positive statements			
Coloured fox (Harper 1956)	(1) Rocky or talus areas. (2) Sandy eskers. Good microtine pop. or waterfowl pop.	Wide variety of food sources	Stable food source	
White fox (Macpherson 1969)	Sandy eskers or dunes. Good microtine or waterfowl pop.	Wide variety of food sources, vegetable and animal	Stable food source	May move to sea-ice to associate with polar bears; may scavenge on beaches
Wolf (Banfield 1954; Kelsall 1963; Harper 1956)	Rocky talus or sandy eskers. Good microtine, waterfowl, or caribou pop.	Good prey pop.	Caribou pop. (1) on tundra and (2) in taiga or forest-tundra	Freedom from poison or aircraft harassment necessary; tundra pop. very sensitive to slight hunting pressure
Grizzly (Banfield 1959; Harington, Macpherson, and Kelsall 1962; Macpherson 1965; Murie 1944, 1962)	Steep hillsides	Good pop. of caribou for carrion; ground squirrel and microtines; lush sedge meadows	Steep hillsides so that a variety of snow types exist for winter dens	Highly susceptible to hunting, harassment, or even "camp protection" killing
Polar bear (Harington 1966)	Requirements still mostly unknown. Breeding range in a few restricted areas; details unknown. Winter range for males, polar pack ice; for females, denning areas			
Weasels (Degerbøl and Freuchen 1935)	Dependent on microtine populations			

Wolverine (Harper 1956)	Rocky, talus, or cliffy areas; or sandy eskers	Dependent on carrion, microtines, and young birds mainly; thus closely linked to saturated caribou, microtine, ptarmigan, and muskox populations		Very wide-ranging; population adapted to solitary individuals; because of wide spacing very sensitive to loss of individuals
Microtine rodents (Pruitt 1966b)	The four main species of tundra microtines show considerable ecological segregation and use virtually all habitats from sedge meadows, cottonsedge tussocks, sedge-birch-heath tussocks, various solifluction slopes, snow-bed vegetation habitats, and talus slopes. They are usually lacking from barren, wind-swept fellfields. The survival of any one species depends on the survival of several adjacent vegetation types since they frequently undergo short seasonal migrations from a relatively exposed summer range to a winter one with thicker snow cover.			
Arctic ground squirrel (Melchior 1965; Degerbøl and Freuchen 1935)	Burrow systems on well-drained ridges or convex surfaces; variety of vegetation types used for food but upland types more important			Well-established hibernation burrow systems on well-drained soil with thick active layer and thick zabois
Hoary marmot (Bee and Hall 1956)	Nothing much known about details of ecology of this species other than need for steep, rocky slopes. Undoubtedly need hibernacula in areas with good drainage, thick active layer, and thick zabois			
Caribou (Kelsall 1968; Pruitt 1959)	Rugged or rolling uplands. Relatively few "traditional" fawning areas. Rutting areas in thin forest-tundra where tall willows and stunted conifers important for courtship display rituals. Requirements of *R. t. pearyi* unknown	Mostly upland tussocky areas; low, lush areas occasionally used, especially by bucks	(A) Very restricted areas of tundra where (1) because of topography snow is relatively thin and soft or (2) excessive windiness has blown the snow away. (B) Forest-tundra or taiga for most of the species	Eskers important as migration routes. Fawning timed precisely to avoid soft, thick snow and/or insect emergence. Lichens and sedges vital
Muskox (Tener 1965)	Unknown, except for requirement of vyduvs, and absence of thick, soft snow	Lowlands, stream and lake edges; dry continental-type climate	Hills or slopes with thin or no snow cover; dry, continental-type climate	Because of low reprod. potential are highly susceptible to hunting (c.f. O. Sverdrup [1904], "New Land, Four Years in the Arctic Regions" R. E. Peary [1907], "Nearest the Pole," and [1917], "Secrets of Polar Travel") Group behaviour poorly known, but so-called "surplus" bulls apparently of importance to calf survival in winter
Arctic hare (Degerbøl and Freuchen 1935)	Usually sandy, hilly or rocky areas	Lowlands, with variety of vegetational types	Upland areas, blown free of snow	

TABLE I (*Concluded*)

Species	Breeding range	Summer range	Winter range	Other
Migrators				
Insectivorous birds (Williamson, Thompson, and Hines 1966; Godfrey 1966)	Regardless of exact nesting range, a variety of habitats usually required for feeding of adults and young	Migration habitat necessary		Food source of terrestrial invertebrates, therefore sensitive to programs of mass distribution of biocides in and near settlements for "mosquito control"
Waterfowl, including shorebirds (Snyder 1957)	Clean water and associated vegetation, varying depths of water and veg. densities	Same as breeding range requirements with addition (for some spp.) of extensive wet meadows and shores	Migration habitat necessary	Many spp. unable to fly during moult, therefore strict protection from harassment needed during this time, usually on summer range. Food supplies susceptible to industrial and human pollution
Raptors (Snyder 1957)	Usually associated with rocky, cliffy country	Extensive areas of lowland and wet areas near nest site, for hunting	Migration habitat necessary	Highly susceptible to environmental contamination because of trophic position, and to loss of young for falconry
Cliff-nesting marine birds (Tuck 1960)	Sea cliffs	Productive area of marine ecosystem adjacent to or available from cliffy coastline	Open ocean	Breeding habitat extremely susceptible to earth tremors caused by man-made explosions. During breeding, extremely susceptible to disturbance by low-flying aircraft or close approach by boats
Caribou (Kelsall 1968; Scotter 1964; Pruitt 1959, 1966a; Banfield 1954)	Rugged or rolling upland. Relatively few "traditional" fawning areas. Rutting areas in forest-tundra where tall willows and stunted conifers important for courtship display rituals	Variety of veg. types, probably upland cottonsedge tussock assoc. most important. Bucks more frequent in lush river valleys	Mature spruce-lichen taiga or forest-tundra. Thin, soft snow cover. Migration habitat necessary	Eskers important as migration routes. Fawning timed precisely to avoid soft, thick snow and/or insect emergence. Lichens and sedges vital

3. There is one important type of winter range: well-drained ridges and hillsides.

When, however, one analyses these requirements in relation to the relative importance of the species to the tundra ecosystem, then one must add to the above:

4. Specialized types of caribou winter habitat in tundra.
5. Caribou winter range in taiga and forest-tundra.
6. Eskers – caribou migration routes, nesting/denning sites for white fox, coloured fox, wolf.

We must not lose sight of the basic characteristics of the tundra food-web: that it is composed of a few species, and is therefore fragile; that the food chains are short and there is a relatively rapid passage of materials and energy along them; that the major part of the second trophic level (first consumers) consists of only three groups of animals – caribou, arctic ground squirrels, microtine rodents; that virtually everything else in the food-web depends on these three groups of animals. Thus the survival requirements of these prime supports of the higher levels of the ecosystem should receive extraordinary consideration. Let us examine them in more detail.

The breeding ranges of caribou and arctic ground squirrels are similar: rugged or rolling uplands with well-drained ridge systems. Whereas ground squirrels are widely distributed in the mainland tundra west of Hudson Bay, caribou fawn in relatively few, circumscribed areas of this landscape type. Kelsall (1968) enumerated some of these vital areas as follows: the vicinity of Kaminuriak Lake, Beverly Lake, Bathurst Inlet, and near Darnley Bay. There are other, less well-known fawning grounds north of the Back and Dillon rivers as well as probable areas on Boothia and Melville peninsulas and in the uplands around Wager Bay. The exact combinations of environmental factors characterizing the traditional fawning grounds still remain largely unknown, but I suspect that among them are: details of the sequence of snow-melt, topographically controlled variations in snow cover, spectrum of vegetation types present, availability of suitable areas to spring migration routes, location of areas in relation to tracts of *Eriophorum* tussocks which produce fresh green shoots and flower buds and thus attract migrating does.

It is virtually impossible to make a comprehensive statement about breeding range for the four principal genera of tundra microtines, but one fact is clear: their optimum breeding habitat lies at a lower elevation and has less rugged topography than is the case with caribou.

The summer range (and winter range as well) of arctic ground squirrel is roughly the same as the breeding range. The same situation holds for other sedentary animals such as the microtine rodents. Caribou, on the other hand, have summer requirements different from those of the fawn-

ing season. Caribou generally move to lower elevations and to less rugged topography during the summer. Probably upland cottonsedge tussock or birch-heath-cottonsedge tussocks are the most important types. In other words, caribou in summer share the same range requirements with most of the microtine rodents. Winter range requirements for caribou are again different. Most of the mainland caribou migrate to the forest-tundra or the taiga, but there are some that overwinter on the tundra, as noted in the table. In this regard, we should stress that the critical range requirements for the high arctic Peary's caribou are virtually unknown. For barren-ground caribou, eskers are of great importance as migration routes. The critical migration routes have been mapped by Banfield (1954) and Kelsall (1968).

It is clear that the only tundra type that is relatively unimportant for animals is flat lowland in winter. It is also clear that there is a marked correlation between those landscape types that exhibit a wide spectrum of snow cover types and their suitability as animal habitats. The more varied the snow cover (patches of exposed ground, or vyduvs, varied drift types, complete cover, hard snow, soft snow, zabois) the more species of animals can use the area.

Protection of "range" as such is no guarantee of species survival. For example, species such as the barren-ground grizzly or the wolverine are extremely susceptible to overutilization. Being top carnivores in the food-web they exist in small numbers, with individuals widely spaced and with relatively weak reproductive potential. Thus the loss of only a few individuals can have a severe effect on species survival. This situation is particularly pertinent in the case of the barren-ground grizzly. To virtually all the present human invaders of the tundra every grizzly is automatically a menace to human life, especially if it is sighted from a camp, and strenuous efforts are made to kill it. It is well within the limits of possibility that the barren-ground grizzly could be extinct inside of five years if a series of oil or mineral exploration camps were successively established at about 50-mile intervals throughout their area of distribution.

We should also note that the polar bear, likewise listed as an endangered species, is susceptible to "camp protection" killing. This species, which is exposed to both the arctic marine and air environments, is also highly susceptible to oil contamination. Although data, either experimental or empirical, are lacking, I suspect a slightly oiled polar bear would survive in the polar sea not much longer than a slightly oiled murre or guillemot.

If there were extensive human activity on any one of the caribou fawning grounds mentioned earlier, or on the migration routes leading to or from these areas, at the times they were in use, I predict that one could detect an immediate and dramatic worsening of the survival situation of this species.

We have seen that the survival of tundra animals depends on the survival of the entire tundra ecosystem as well as severe protection to certain critical areas. From isolated experiences we also know that tundra animals can exist perfectly well in relatively close proximity to human activity and settlement if they are protected during critical times and are not exposed to the results of certain specific operations. I have seen waves of migrating caribou pass within a few yards of tents and cabins, causing pandemonium among the tethered sled dogs. I recall reading once in a Russian school childrens' magazine "The Young Naturalist" of how a schoolteacher in one of the Soviet arctic towns took her classes on weekly hikes to observe the growth of two baby polar bears in their snow den near town. (Incidentally, can you imagine this happening anywhere in the Canadian or Alaskan arctic?)

Mining, oil extraction, shipping installations, or air strip facilities are highly automated operations, and will in future use only minute parcels of land, with very, very few human accomplices. Not even in the wildest dreams of the exploiters or promoters could such operations cover more than, say, one or two per cent of the actual land surface (Pruitt 1962). The remainder of the tundra can either continue to produce wildlife and other renewable resources or it can become, very quickly, a biological desert.

The basic knowledge to ensure the perpetual presence of the critical survival requirements is for the most part already available today. There are some gaps in our knowledge, to be sure, but concentrated research can fill these gaps in relatively short order. (Some of the more pressing research needs are: a delineation of all caribou fawning grounds and clarification of the factors that characterize them; a clarification of the winter and spring ecology of muskox; a complete ecological and behavioural study of Peary's caribou; population dynamics and ecology of the barren-ground grizzly, wolf, and wolverine.) The missing link in the struggle to save the tundra is the public will to put the knowledge we already have into operation.

First, there must be recognition, by all levels of government, and by the public, that the tundra ecosystem is truly fragile. The taiga ecosystem, on which the caribou depend in winter, is perhaps even more fragile. Boreal ecologists have been hammering on this theme for years but there is little indication that our efforts at public education have achieved any success. For example, after the Cooperative Caribou Investigation of 1957–8, vigorous representations were made to government to institute fire protection on the critical winter range, but today the fire protection picture on this range is essentially unchanged (i.e. non-existent).

Second, we must honestly recognize that the technological ability to destroy an ecosystem has far outstripped the development of govern-

mental machinery for control of the exploiters. We must have a moratorium on northern exploitation in order to give the democratic process a chance to catch up. What we have now is, quite frankly, a dictatorship by the exploiters.

Third, we must recognize that profit-oriented commercial organizations have no interest in anything on the tundra but the immediate monetary return on their schemes. Some companies do, indeed, publish beautiful advertisements that extol their corporate concern for conservation in the north, but when a cat train is sent out, a drill rig moved, the route and timing are dictated solely by economics and engineering factors. Self-control or self-policing has not worked in the past and I see no reason to believe it will work now.

Therefore strong governmental land-use regulations are absolutely necessary. There are certain basic requirements that the regulations must meet in order for them to be effective: (1) they must be ecologically sound, and (2) they must be rigorously enforced.

In November 1969 the federal government assembled a panel of ecological consultants to consider such regulations. I was honoured to be a member of that panel. After much deliberation, argument, and correspondence we formulated a set of regulations and stipulations that, if followed, allowed multiple use of all resources in the north, yet prevented the fragile, renewable resources from being destroyed in the process of extracting the non-renewable resources. Among other requirements, we stipulated a maximum ground pressure of 70 pounds per square inch for cross-country vehicles, restriction of the minimum turning radius for tracked vehicles in various soil-permafrost types, no blocking or disturbances of moving water, and ice bridges to be dynamited before break-up. All unburnable trash, including oil drums, excess machinery and buildings, seismic wire, must be removed. We required all exploration information to be pooled with results deposited with some government agency and made available to everyone so that the exploration of any area need not be repeated. We required that all camps be equipped with incinerators, using excess fuel, and all garbage, trash, and sewage be evaporated and burned, the residue being bagged and flown out on deadhead supply flights. We also prohibited any vehicular travel in streams or marshes when unfrozen except by canoes, boats, or airboats. We prohibited camp operation in caribou fawning or rutting areas at those critical times of the year. We prohibited the use of wildlife by transient people in any way. We prohibited the keeping of firearms except one by a specified individual in each camp for camp protection, these individuals to receive training in techniques of scaring, trapping, transplanting, and removal of problem wildlife. We prohibited the feeding, baiting, or luring of wild animals around camps. We prohibited the use of vehicles or aircraft to chase or

harass wildlife. We required that camps be equipped with electric fences to repel bears, fences designed after successful polar bear fences perfected in northern Manitoba. We required that all fresh garbage and food stocks be kept in closed containers and that garbage be disposed of daily.

This gives an idea of the kind of regulation of human activity required to safeguard the integrity of the tundra ecosystem. Note that these regulations do not prevent exploration or extraction of oil or minerals. Our proposals met opposition and official inaction because they would reduce the profits of the oil and mineral companies. Canadians have become so accustomed to thoughtless destruction of their tundra heritage that they have forgotten the basic tenets of civilized conduct when in the north.

The government's own schedule of events called for the regulations to go into force at the end of April 1970, so that the exploitation activity during the summer could be controlled. Delay after delay after delay and successive mutilations of the regulations and stipulations have brought us into the 1970 exploration field season with the tundra again unprotected and, at present writing, the regulations and stipulations are still not in force.

One of the worst mutilations of the regulations was the loss of a required performance bond. No matter how perfect the regulations, without a performance bond there is no corporate entity which can be held accountable and responsible for violations. Companies that engage in northern construction are, in general, peculiarly ephemeral things. They form and then go into bankruptcy and quickly re-form under different names while the bulldozers scarcely cool off. Without a performance bond these will-o'-the-wisps cannot be held to account.

What are the alternatives to strict regulations and their rigorous enforcement? Hopefully we should be able to learn from past experience. Without regulations and enforcement we have seen the rate of destruction by fire of winter range of caribou increase in the past 20 years to three times the pre-whiteman rate and caribou numbers decline from a pre-contact level of almost 1¾ million to the 1960 low of about 200,000. Without regulations and enforcement we saw the muskox dwindle from an estimated pre-contact population of perhaps 1 million (Seton 1929) in continental Canada to about 500 (R. M. Anderson in Hoare 1930; Hone 1934). After 1917, with strict regulations and rigorous enforcement the muskox have recovered to their present continental population level of some 1,500 individuals. We can say, with considerable confidence, that without strict regulations and rigorous enforcement the tundra ecosystem will be modified the same way the deciduous forest and the grasslands ecosystems were modified. Without regulations and enforcement we shall see the loss of the barren-ground caribou, the barren-ground grizzly, the wolf, wolverine, polar bear, several species of waterfowl, several species

of raptors, and the cliff-nesting marine birds *as usable renewable resources* (Novakowski 1970; Godfrey 1970). I doubt if we shall ever allow any more North American species of birds or mammals to become extinct, but there is a vast difference between the presence of a pitiful remnant of a species and a healthy population that can be cropped or used for human benefit. The caribou, in their present condition, are hardly a usable resource, since they could furnish a crop of scarcely 20,000 animals annually, yet if their population were to recover to about 1,000,000 animals (about half of aboriginal levels) they could be cropped at the rate of about 150,000 animals per year. Based on dollar values of meat alone this would be an annual increment of some eight and a quarter million dollars to the national economy. The value of skins and other products, as well as tourism and sport hunting values, would be in addition to this sum (Kelsall 1968).

Now, eight and a quarter million dollars per year is big-time money, no matter how you look at it. Remember that a high percentage of this is net, since capital investment is nil and management costs are minimal.

Of much greater importance to the future of mankind than the annual eight and a quarter million dollars would be the annual increment of some 15 million pounds of protein and fat to the world's supply, for, make no mistake about it, in the forseeable future we are going to need every calorie we can get. It is the height of folly to continue on our present course of narrow, single-use exploitation of the north. With care, tender loving care, we can extract oil and minerals and also produce wild meat, fur, berries, fibre, and other renewable resources. But the time has passed to consider the problem as something to be worked out in the future. The situation is now one of crisis. We must have immediate public action.

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Industry and the Arctic Environment†

With civilization's demand for ever-greater quantities of energy and materials, the search for resources has spread to the most remote and inhospitable parts of the world. Today Canada uses six times the petroleum it did 20 years ago, and Canadians now use more petroleum per capita than any other people in the world. Petroleum is an important factor in our environment – at the well-head, in the ship or pipeline, in the automobile where it helps pollute the atmosphere, or in the thermal power plant, where it pollutes the atmosphere rather less than some other energy sources.

This paper will comment on the factors involved in environmental protection, and the protective measures taken by Canadian industry in the finding, development, and transportation of oil and gas. The petroleum industry's prime responsibility is to supply Canadians with the energy and the chemicals they need, at the lowest cost and with the least possible disturbance to other life factors. The effects of disturbing the environment – the Canadian scene – often cannot be measured in dollars, and Canadians – especially younger Canadians – will not accept dirty rivers, scarred landscapes, or polluted air. Yet if we want to go on using packaged goods, and growing foods or producing minerals for ourselves and for others, we must face at least some disturbance of our environment, some alteration of our air, land, and water from their natural state. Canadians must decide what their priorities are and what balance they really want between nature and technology. If we increase our use of resources, or even stay at our present level, the best of intentions and the strictest of regulations cannot wholly

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prevent an adverse effect on our environment. What we *must* do is stop unnecessary damage, and develop methods and procedures that will prevent most serious accidents, and will lessen the impact of any that do occur.

Resources are not inexhaustible, and their wise use over a long term must be planned – not in a piecemeal way, but by examining the whole system and weighing a plus here with a minus there. For any product, from high-test gasoline to plastic garbage bags, the specific costs of environmental protection will in the final analysis be borne by Canadians as consumers. In most cases we cannot afford not to protect our environment, yet since our products compete in the world market-place, the scale of thinking must be the national purpose.

ARCTIC DEVELOPMENT: THE LAST FIFTY YEARS

Today, the focus is on the Canadian arctic and the exciting new developments there. As long as I can remember, Canadians have been talking of the need and the challenge of developing the Canadian north. A few years ago there was the "vision of the north," but most people did no more than talk about the vision. Both mining and petroleum interests, however, have been engaged for many years in a slow, unromantic development of parts of the arctic. Back in 1919 Norman Wells was discovered, a small oilfield with recoverable reserves of about 60 million barrels. In 1936 a small refinery was started there, and it has supplied local fuel requirements ever since. Then with the war came the Canol Project for further development and exploration work at Norman Wells, and the early forties saw a pipeline flung 660 miles across the arctic to Whitehorse. During the 1950s there was exploration activity on the Eagle Plains, and in the 1960s, all down the Mackenzie Valley. Then last year all this was overshadowed by the wild rush to Alaska sparked by the glamour and excitement of Prudhoe Bay. This year's discovery of oil at Atkinson Point caused little stir, being received as just another step in the development of the arctic.

Over all this time, there has been steady progress in learning to work in the arctic. For example, in the early days damage to the tundra was extensive, particularly in Alaska. This was because the bulldozers and high-ground-pressure military vehicles that were used stripped the moss off the icy permafrost. A little over ten years ago, industry developed low-ground-pressure tracked vehicles for exploring in muskeg. These work well on permafrost in winter, and tests in Alaska last summer showed that they can travel over tundra without damaging it. More tests are planned for this year in the Canadian arctic. These new vehicles have been found useful all around the world; several are at work under similar conditions in arctic Siberia.

Since 1964 most companies have voluntarily limited geophysical exploration to the winter season, to avoid damaging the tundra and to lessen the disturbance of wildlife. Again, such things as permafrost foundations, road-building, service lines, storage tanks, and drilling have been of concern for years, and there has been great progress. Some of the problems have been solved, but there are many more ahead. What should be done?

The need now is to look at the long-term plans for the arctic, to define what new problems there will be next year, in the next 10 years, and in the next 30 years. What will be the effect on the arctic environment? There will be pressure to develop and extract arctic resources – not from big companies, not from tax-hungry governments, not from politicians, but from people of all sorts, from the millions who want only enough to eat to the hundreds of thousands who use more energy and material each year, who waste more each year, who want a bigger automobile than their neighbour's, or a second or a third automobile, who cry about polluted air while they blow cigarette smoke in your face. If these pressures are to be resisted, or their impact minimized, then there must be a master plan for orderly arctic development. Why can't we begin to draw that master plan now? Why can't we set aside areas for parks and wilderness, why can't we draw boundaries for game preserves, why can't we dedicate lands for oil exploration and development, and for mining? Why can't we lay out transportation corridors? There is good basic knowledge of the geology, the climate, the renewable resources. The area has been mapped. I can't agree with those who say, "Let's stop everything while we do research." Any good researcher will always find new problems – he will never agree he has all the answers. I can remember at least 28 years of *talk* about arctic development – do you think we shall have all the answers in another thirty? Let's stop talking and *do something* about it.

You may ask, "*Who* is going to do something?" or perhaps raise the cry, "We can't compete with all that money from industry!" One of the most heartening factors in the latest moves in the arctic has been the new cooperation among government, industry, and the academic community. Representatives of all three are meeting around tables, discussing their problems, and *doing something*. One example of this is the program of tundra productivity under the auspices of the International Biological Program, covering Devon Island and extending to the Mackenzie Delta – a program of basic research expanded to include manipulation studies, which are studies of, for example, the effects of small oil spills. This program was agreed upon by representatives of government, industry, and the universities with support coming from the National Research Council, from university grants, and about one-third from industry. This sharing of costs is good, but perhaps even more important is the sharing of ideas, the planning, and the broadening of the research effort.

Another excellent example is the program of research being undertaken by the Department of Indian Affairs and Northern Development to back up their land-use regulations. This is a program hammered out by representatives of government, universities, and industry. Most of the work will be applied research with university people acting as consultants or project leaders, but advice and logistic support will come from industry and from other government departments.

With this kind of cooperation and participation, I believe that the long-term needs and safeguards for the arctic can be assured. My only word of caution is to recommend that most of the planners should have lived in the arctic and have participated in the research and development that have so far been accomplished. We have too many people talking of problems and solutions who have never been near the arctic, who are at best "three-week experts."

Where do we start? As a point of departure, let's first set aside a percentage of land for national parks – say five times the percentage we now have in southern Canada. What land should we choose? The Yukon has some of the finest scenery in the world. Select areas there and in the Mackenzie and British mountains in the Northwest Territories. Perhaps we need a pingo park along the arctic coast, and areas all across the Pre-Cambrian. If we err, let us err by dedicating too much to parkland. Let us get the best advice on where more game preserves are needed, and then set them up – with regulations that will effectively preclude harm to wildlife.

Let us look next at the major basins of sedimentary rock and predict where reserves of hydrocarbons are most likely to be found or, more correctly, the centres of gravity of those reserves. Then let the government, with industrial and academic guidance, set aside transportation corridors along which to move products to market. If some of the reserves happen to be along the Mackenzie, then let's see that the oil lines, the gas lines, the highways, the communication links, and the airports are all in one transportation corridor. Let us begin now to examine how accidental spills may be cleaned up and their effects minimized, so that these hydrocarbon resources can be made available at a minimum cost to those who need them. Let us weigh the degree of damage that may be expected from a marine shipping system against that of a pipeline. And let those of us who are engineers be sure that we have the information we need to design pipelines, or ports, or plants, with a maximum of safety. This is not a purely unselfish goal: true, we protect the environment; but, more importantly, we cannot afford to have failures in the arctic!

Academic, government, and industrial personnel will be able to cooperate more usefully if each group is aware of the other's problems and capabilities. Such awareness might come from summer courses, given in

the north and covering the whole gamut of arctic science. We have suggested that the University of Alberta give such a course at Inuvik beginning in 1971. Its aim would be not to extend our expertise but to disseminate what is known, to acquaint more people with arctic progress, and to act as a forum. Such courses might also be given at Yellowknife, or Dawson, or Resolute. McGill University has pioneered this kind of work with its Geography Summer School, Arctic Seminar given at Stanstead. At this stage the courses should not be too narrow, and should cover such disciplines as geology, ecology, anthropology, science, and engineering. Specialization will come naturally as we learn more and more.

MAJOR PROBLEMS IN THE ARCTIC

What are the major long-term problems of the arctic? The first is people: How can the people of the north be brought into the development of their country? In the western arctic this is already being done: Richard Hill, mayor of Inuvik, says there is now virtually no unemployment there. The oil industry employs well over 100 local people directly and many more indirectly; it could use still more were they available. Perhaps it is an oversimplification, but the great need here seems to be for education. This need is being well met at primary and secondary levels by government schools, and supplemented by technical schools and on-the-job training. The oil industry, in cooperation with the government, has set up a committee to coordinate the employment of native people. All the same, there are bound to be regional disparities just as in the south. The answer isn't to move people, either: I am sure it would be far more distressing for a northerner to move from, say, Baker Lake to Inuvik, than for a westerner to move to, say, Toronto – although I am equally sure the man from Baker Lake would prefer Inuvik to Toronto!

The second long-term problem is water, though this land contains over a third of the world's fresh water, plus other vast quantities held in muskeg, which would be desert if the soil were not permanently frozen. We know that there will be pressure in the future to tap these arctic water resources. Let us set about taking an inventory now; let us thoroughly understand the water regime and the key areas for wildlife, so that if in the future Canadians need this water, we shall all understand what the true costs are. We must know exactly how surface (muskeg) disturbance, land reclamation, and watershed management will affect the water resources.

The third big problem is the rest of the environment, the ecology of the arctic. Specifically, we should outline and draw up protective regulations for the key areas used by migratory waterfowl. We should limit development to seasons when these will not be affected, and should minimize or

eliminate installations which now or in the future could harm the over-all population of bird life. We should take the same care with regard to marine life and to arctic mammals. Industry is already doing this on a voluntary basis, but we need guidance; we would welcome strict, sensible regulations on the use of land and water, regulations that will safeguard the environment and ensure that all who develop the north live by the same rules.

The fourth and last problem is engineering: the climate, the permanently frozen ground, the terrain, the long distances, all offer new challenges to the engineer from the south. They restrict his freedom of design, they change the economics of his projects so that the familiar rules of the south no longer apply. Those who have worked in the arctic have learned what the limits are; their concern is that, with increased arctic development, people without their experience will make the mistakes they did. In the oil industry, the greatest concern must be in the areas where a mistake would release large quantities of oil, as in an oil-well blow-out, a pipeline break, or a marine disaster. Economics as well as concern for the environment dictate that every precaution be taken in engineering design at this stage. Such work should be done by Canadians, and it *will* be done by Canadians if our academic institutions train the requisite number of people and establish the kind of excellence in the field of arctic engineering that Canada needs.

F. KENNETH HARE*

The Tundra Climate†

The tundra is there in our north because it is the highest response the biota can make to the energy and water delivered, in the presence of stresses that make all life marginal. It is hence easy to assume that it is the tundra, and not the climate, that is imperilled when the stresses are increased. I propose to challenge this view, and to argue that the climate itself may be fragile, and needs our protection.

Tundra – the treeless but complex vegetation carpet of arctic and alpine lands – lies between the northern boreal forest limit and the permanent ice-caps that still cover Greenland, and that used to cover most of Canada. There is hardly any antarctic tundra, so we are speaking here about the Northern Hemisphere, in which resource exploitation is also concentrated. It is broadly true that in lands where July has a mean daily temperature below 13° c there will be tundra patches, and where it is below 10° c there will be no trees. Between these rough and ready lines there is forest-tundra, the *lyesotundra* of Russian ecologists, the land of interpenetrating types that our own Jacques Rousseau calls, picturesquely, the *hémi-arctique*.

These correspondences tell us little about the actual mechanism of control, but their world-wide consistency at least shows that something in the physiology of the biota requires a certain level of heat storage in tissues, air, and soil, because temperature is a storage parameter. I am not going to speculate about that physiology, because there are ecologists present who know something about it, and I am only a climatologist.

I can offer, however, an answer to the question: Does radiative energy delivery to the surface affect the issue? Climatology is in the age of radia-

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tion studies, and it is natural to ask this question because one can at least plausibly argue that the rate of energy delivery, rather than the energy level, is critical to the life process. One of my students, J. E. Hay (1970), has just completed an estimate of the net radiation income over Canada and Alaska, and I shall speak briefly about his results.*

Although the summer is short and the solar elevation at noon is low, the long arctic day permits a high income of solar radiation so that the total received in the tundra areas is from two-thirds to three-quarters that recorded in southern Canada. The surface albedo is high, however, so that the fraction absorbed in the north is substantially less. In Table I I have given representative values of this parameter. Along the northern tree-line (which of course is in fact often a wide zone) the value of about 55 kilocalories per square centimetre (kilolangleys) per annum seems to apply, and the lowest values in the Canadian tundra are probably near 35. Highest values in the country slightly exceed 90 kly.

TABLE I

Values (very approximate) of the various annual radiative fluxes at the Canadian and Alaskan tundra surfaces (data from Hay, 1970)
(kilolangleys per year; all values positive)

Spatial feature	Global solar radiation	Solar radiation absorbed	Net radiation
Arctic coast, Canadian Archipelago	70	35–40	0–5
Northern limit of trees			
(i) Alaska	80–85	55	15–20
(ii) Keewatin	85–95	55	15–20
(iii) Labrador-Ungava	90–95	55–60	18–25
Southernmost Canada	130	90	40

To get the *net* radiation income of the surface one has to subtract the net long-wave cooling due to exchanges between surface and atmosphere (and space, to a limited extent). I have added to Table I the range of net radiation values that seem to hold. At the tree-line, some figure between 15 and 20 kly per year seems to apply, though Sitka spruce groves exist in the Kenai Peninsula within this range, and the coastal tundra (possibly not spontaneous) of Labrador-Ungava has values near 25, on both east and west coasts. Most remarkably, however, no station in Canada or Alaska has, according to Hay's calculations, a negative annual net radiation income. The tundra surface is not, on a year-round basis, a radiative heat sink, the prolonged cooling of winter being a little more than offset by the short but strong heating of summer.

Budyko's values (1958) for the same radiative fluxes show that com-

*The slides used are not reproduced here because they have not yet been published by their originator.

parable figures hold over the Eurasian tundra, though forest patches survive in eastern Siberia at annual net radiation values well below 15 kly per year. It is probable that it is the net *positive* radiation income of summer that really counts in these matters. If so, the disparity between the two hemispheres is lessened.

We can thus move fairly close to a definition of the tundra climate in thermal terms: it is one where the annual net radiation income is between zero and 15 kly, and where mid-summer mean daily air temperatures are roughly in the range 3° to 10° C. The boreal forest lies above 13° C and 20 kly per year, and between lies the forest-tundra. I repeat that these geographical correspondences are nothing more than statements of fact, and in common with all other northern specialists I yearn for the day when we can replace them with a quantitative account of the ecosystem relations. We are still far from it.

Precipitation on the tundra lands is hard to measure. Summer rains – largely between early July and late August – are quite frequent but rarely heavy. Many of them fall from travelling cyclones of the arctic frontal belt, which stretches along the forest-tundra from the White Sea to Hudson Bay. Undoubtedly we miss some of this rain with our gauges, because of high winds. We miss still more of the winter snow. In 1960 the Meteorological Service of Canada replaced its traditional measuring stick with Nipher gauges, and it has been zealous in extending the snow-course network across the country. Nevertheless the impression persists that in the windy tundra and forest-tundra areas – and open weather station sites are even windier – it is almost impossible to measure the snow that on natural surfaces is trapped in topographic pockets and swept clear of the rest. Work by Findlay (1969) at Knob Lake, near the southern limit of the forest-tundra, suggests an undermeasurement of rain by 15 per cent, and of winter snow by 26 per cent.

It is very likely, in fact, that the winter snow-pack of the tundra contains substantially more water than climatological measurements suggest. Most of the snow comes early, in September and October, and mid-winter is largely snow-free (though blowing snow reduces visibility about a quarter of the time across the central arctic islands and Keewatin). More falls in spring, just before the thaw. The essence of the tundra snow-pack, however, is its patchiness, its nine to ten months life, and its high relative density – generally over 0.3 – because of wind packing. As all northern ecologists know, the wind-drifting of the cover creates a patch-work quilt of site conditions, from surfaces exposed all winter to intense chill and drought to those buried deeply and comfortably beneath a compact blanket. The patchiness is also critical in geomorphic and periglacial processes. We need an intensive study of the tundra snow-pack. Carl Benson (1969a) in Alaska has shown the way, and we have in this coun-

try, at the National Research Council's Division of Building Research and in the Climatological Division of the Meteorological Service of Canada, outstanding skills that could do this job, if we had the resources in money and time.

These topics – thermal and moisture conditions – have been the traditional things considered when northern climates are discussed. I am going to turn now to the less obvious matters in which the alleged fragility of the climate resides.

The first of these lies in the great hydrostatic stability of the surface airstreams. Powerful inversions cover the tundra and boreal forest most of the winter and some of the summer. These may be true surface inversions with dead calms, common in valley-sites, or there may be a shallow surface mixing layer, perhaps 500 metres in depth, when there is strong wind, or when the air has recently passed over open water. In either case the arctic airstreams have a much lower capacity to remove atmospheric contaminants by turbulent diffusion than do most other airstreams. They are hence vulnerable to pollution by smoke sources.

The best-known examples of this vulnerability are the ice fogs of winter in the towns of the northwest, above all in Fairbanks, but also in Whitehorse, Yellowknife, and Inuvik. If other towns are built in these areas they will be prone to this hazard. Benson and his associates (see, e.g., Benson, 1969b) have studied the Fairbanks phenomenon for many years, and we know quite well what has gradually rendered this small forest-girt town one of the most polluted places on earth. It is a horrible example that we can learn lessons from.

In dead calm weather in winter – common in the western arctic, from the great northern lakes to the Bering Sea – intense surface inversions persist for many days, with surface temperatures well below −30° C. Such air is able neither to absorb water vapour, nor to disperse particulate matter. Both are discharged into it from numerous artificial sources: thermoelectric generating stations, domestic furnaces, car exhausts, aircraft engines. Cars will start and run below −30° C these days, but there is a natural tendency for the driver to leave the engine idling while his car is parked. Nuclei for the crystallization of ice exist in abundance below −35° C, so dense ice fog forms, and the town becomes shrouded in the nastiest gloom the atmosphere is capable of – obscure, frigidly cold, and stinking with the various combustion products that cannot disperse. The great increase in aircraft movement through Fairbanks airfields has compounded the problem. At temperatures above −35° C conditions are less foggy because of the apparent lack of freezing nuclei, though the other pollutants still accumulate.

This inability of the winter atmosphere to disperse pollutants is more than simply a nuisance to town dwellers. There is also the question of fall-

out. Evidence is accumulating that effluent substances, and such poisons as lead and arsenic, tend to be precipitated or deposited close in to the emitting site, so that one visualizes a sort of metamorphic aureole of contaminated soil, vegetation, and surface water gradually ringing northern towns (Kay 1968).

With these visible things before us, we are right to be apprehensive about the prospect of the growth of more northern towns until we have learned how to run them without ruining their surroundings and exposing their citizens to discomforts and health hazards. The northern winter is tough enough without our bungling. The prospect of numerous tankers emitting water vapour in northwestern waters, for example, promises dense ice fog in the channels and in harbours.

The ice fog and air pollution hazard – the consequence basically of the windlessness and strong radiative cooling – is mainly a feature of valley sites in the western arctic and Alaska. Canada's eastern arctic – mainly Keewatin, Ungava, and the Archipelago – is windier, and prolonged periods of stagnation of the surface air are much less frequent.

On a far larger scale, it may be that the tundra climate of today is threatened by another and more pervasive form of pollution. I refer to the steady build-up of atmospheric carbon dioxide, which is increasing at the rate of about six parts per million per decade, from the present value of 320 ppm, primarily as the result of fossil fuel consumption. It is reasonable (though by no means unanswerable) to speculate that the concentration may raise the mixing ratio far above its present value. Doubling the ratio might raise world temperatures by 2.4 deg C (Manabe and Wetherald 1967). If this were to happen, the stability of the Arctic Ocean's pack-ice would be imperilled, and it is quite likely that the pack would disappear. Even the minor oscillation of world temperature by about +0.6 deg C between 1880 and 1940 was accompanied by a probable thinning of the pack by about 15 per cent, and a marked reduction in its export along the East Greenland current; and the downswing of temperature since 1940 of about −0.3 deg C has been accompanied by a great increase in that export, as Iceland has reason to know to her cost. Significant swings of world air temperature are likely to produce marked variations in the thickness, health, and behaviour of the arctic pack.

It may seem odd that I should stand before you and say that we cannot do without the arctic pack. If it were not there, and its outflow did not block the western channels of our Archipelago, their navigation would be simple. The winter ice that would still form in those channels could be more readily handled by ice-strengthened vessels, and the arctic basin itself would be open to year-round navigation. Why then should I be apprehensive?

Simply this: the entire thermal economy of the Northern Hemisphere's

climate, and hence its zonation, depends on the presence of the pack-ice, whose high albedo and low thermal conductivity dominate present-day conditions. If the pack is taken out, everything must be drastically changed, though we cannot yet predict the details. I can, however, illustrate the inevitable effect on the circulation of the atmosphere. The present-day zonal circulation of the atmosphere – mid-latitude westerlies, tropical trade-winds – derives its energy from potential energy differences of which the pole-equator temperature difference is a crude measure. An open polar sea would reduce that difference in mid-winter from the present-day 60 deg C to about 35 deg C. This would bring about a sharp reduction in the momentum of the entire zonal circulation, probably by nearly half (Rakipova 1966), and alter fundamentally the paths, frequency, and intensity of precipitation-forming disturbances.

Respectable but highly qualitative theories of climatic change have been erected around this idea, and there have been attempts to be more quantitative by such people as Budyko (1966), Rakipova (1966), Fletcher (1966), and Vowinckel and Orvig (1967). Actually to test the hypothesis, and to predict its probable effect on the zonal temperature and precipitation distribution of the earth, complex dynamical models of the atmospheric and oceanic circulations, and of their interaction, are needed. The models that do exist cannot do the job properly. So we can only plead for time. Since we are certain that the effects would be drastic, and possibly deleterious, we are on sure ground in asking that attempts to alter the stability of the pack-ice wilfully (as has been suggested) or accidentally – for example by diverting rivers draining to the arctic – be not made until we are a lot closer to certainty about details.

Of a few things I am quite sure. If the ice ever does leave our northern shores, the effect on our northern climate will be immediate and drastic. I would expect much warmer but cloudier winters, with a huge increase in winter snowfall in northern areas. Summer might be a little warmer, but again cloudier. In all probability plateau and alpine glaciers on the arctic islands and in the hilly areas of Labrador-Ungava would again expand. The tundra and boreal forest climates would be quite different, and the present-day ecosystems would be drastically altered, though I cannot say how.

I mention these things not because I expect them to happen, but because hard-headed scientists can now see them as possibilities. The northern climates are stable only as long as the sea-ice is stable. And we have concrete evidence that the arctic pack's stability is fragile (Hare 1968).

I hope I have said enough to indicate that the northern climates cannot be taken for granted. They are in delicate equilibrium, and it is clear that man's handiwork may disturb that equilibrium.

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J. D. IVES*

Arctic Tundra: How Fragile? A Geomorphologist's Point of View†

Until recent years the arctic tundra landscapes, and for that matter the alpine tundras also, have been only slightly affected by twentieth-century technology. New discoveries of vast mineral resources, principally oil in northern Alaska and northwestern Canada, and iron ore and asbestos in the eastern Canadian arctic, have wrought a dramatic change in the chances that the North American arctic will remain a great sanctuary for small groups of native peoples, wildlife, and natural scientists alike. This change has been furthered by wide-ranging oil and mineral exploration, especially in the Canadian archipelago. Counterpoised to the large-scale industrial exploration and preparations for exploitation has been the recent ground swell of public concern for mankind's progressive and deleterious impact upon the environment of the entire earth. The onus is now upon industry, government, university scientist, and public to attempt formulations of answers to the questions: How fragile is the tundra? What is its bearing capacity relative to large-scale technological invasions? How far can we evaluate totally "undisturbed" tundra landscapes on the one extreme, and the prospective ruthless disturbance for the sake of a short-term gain on the other, and the whole range of compromises between these two extremes? In large part such evaluation will rest upon our ability to develop formulae that will embrace a dollar assessment of the aesthetics of landscape; this in turn will involve a multiple approach as different segments of Western society have quite different, and sometimes conflicting, aesthetic appreciations.

Dr Lawrence Bliss has ably illustrated the plant ecologist's view of

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the fragility of the tundra ecosystem: in an arctic tundra setting, there is a low level of plant productivity and a very small total number of individual species, and intricate interrelations exist between plant cover, energy exchange at the surface, and stability or instability of underlying frozen ground. This approach also indicates the extensive area of common interest between the plant ecologist and the geomorphologist within the context of tundra fragility. First, it must be emphasized that the arctic zone comprises a great range of landscape types, probably as great a range as will be found in any of the other major latitudinal life zones. From an engineering point of view, the wet tundra lowlands of the Alaskan north slope can be regarded as being as different from the glaciated rocky topography of the Baffin Island plateau, for instance, as they are from the hot desert environments of North Africa. Any consideration of arctic geomorphology in the present context, therefore, will revert invariably to a consideration of ground temperature conditions and soil types. The extreme case is perhaps the Alaskan north slope, characterized by extensive areas of wet tundra of low relief, underlain by extensive thicknesses of permafrost with a very high ice content. This case is the more important precisely because this same area may well be bisected by a 48-inch-diameter pipeline fabricated to carry oil at a temperature of 160° to 190°F. On a theoretical basis the problem is quite simple: in areas where the overburden is of fine to medium grain, that is, areas with frost-susceptible soils, the ice content of the permafrost may be as high as 50 to 75 per cent. Disturbance of the energy balance at the surface through destruction of the plant cover by mechanized transport could cause serious thermokarst development. Lachenbruch's (1970) recent theoretical study of the impact of a hot pipeline in such a situation is quite dramatic. Presumably, however, the decision to elevate the pipeline (thus ensuring insulation of the ground cover), based upon a detailed permafrost survey, will provide a technologically adequate solution. But a source of gravel for road construction over terrain underlain by permafrost remains a problem and the potential for geomorphic catastrophe is real.

The foregoing comments emphasize the need for an accelerated permafrost research program. Much basic scientific knowledge and engineering know-how has been accumulated since the Second World War. The fact remains, however, that even the broad geographic limits of permafrost distribution in North America are known only on the basis of scant reconnaissance surveys and the gross application of known crude relationships between mean annual air temperature and probable mean annual ground temperature, derived largely from the Soviet literature (Brown 1960). Perhaps this knowledge is sufficient to provide a preliminary foundation upon which detailed and more sophisticated surveys can be advanced in those areas where potential technological impact demands. Yet the whole

question of tundra fragility, or rather the varying degree of fragility from one area to the next, can be answered only on the basis of a vast increase in the amount of permafrost data and the understanding of those data. It is perhaps not altogether insignificant that the ratio of government-employed permafrost scientists between Canada and the Soviet Union is approximately 1:1,000. Does not Canada have sufficient resources and vital northern interests to warrant the establishment of a chair, or department, of permafrost research at one of the large universities that already has a strong arctic research reputation? It is remarkable to me that probably the most accurate map of permafrost distribution on the eastern Canadian mainland (Labrador-Ungava) is my own (Brown 1969), which was extrapolated from a minute amount of ground temperature data, and Hare's map of the cover types of the peninsula (Hare 1959; Ives 1963).

The fragility of the tundra (F), therefore, may be regarded as roughly directly proportional to the ice content of the permafrost and inversely proportional to the mean annual ground temperature, i.e. $F \propto i/t_g$, where i is the percentage ice content of the permafrost and t_g is the mean annual ground temperature.

In the extreme case of bed-rock outcrop, such as is typical over wide areas of the eastern arctic that are underlain by granite-gneisses of Archaean age, and which have been extensively glaciated, tundra geomorphic fragility is very low indeed. Intermediate surface types are coarse-grained sediments, glaciofluvial outwash, eskers, coarse tills, boulder fields of varying forms and origins. Extreme fragility will occur where medium to fine grained sediments and organic soils abound and where the mean annual ground temperature is close to 0° c. Disturbance of the surface cover will then produce extensive thermokarst and, probably, rapid thinning, or complete disappearance, of the permafrost.

It must also be borne in mind that natural disturbance of the tundra surface is occurring in many areas. In the preceding paper Dr Hare has introduced the notion of the fragility of the tundra climate and man's ability to upset a delicate balance at the earth's arctic surface inadvertently by merely continuing to pump pollutants into the atmosphere without ever setting foot on the tundra. The early twentieth-century warming trend has resulted in an extensive northern shift of the southern limit of permafrost in the Soviet Union and the formation of thermokarst across wide areas of the arctic. But disturbance on quite a large scale is also caused by wave action on freshwater lakes and along the sea coast whereby earth banks are undercut and ground ice exposed to melting (Mackay 1966). This form of disturbance will occur without climatic amelioration. An excellent example of this type of geomorphic fragility has been described and photographed by Lamothe and St-Onge (1961). These points serve to

emphasize further the delicate state of balance that can be grossly overturned by human impact.

It must be admitted that modern engineering technology can probably overcome the geomorphic problems, but the financial cost would be high. Thus it becomes a pressing concern that organizations intent upon making a profit from short-term extraction of non-renewable resources work under sufficiently strict controls to ensure that economic short-cuts in the name of corporate efficiency are not taken at the expense of future generations. Perhaps even more insidious in a fragile tundra setting is the seemingly natural tendency of the extractive industry to operate on a trial-and-error basis. A good example is the manner of construction of many of our northern towns. Residents of Schefferville, northern Quebec, for instance, may initially be enthused over the fine houses, but they will soon come to curse the utter treelessness of the entire townsite leaving them open to blowing snow and very low sensible winter temperatures and the all-pervading red iron ore dust of summer.

I would like to make a final plea to the natural scientist: we must accept a pressing obligation to provide government and industry with the "applied" results of our research, oftentimes in a rough and ready manner, without awaiting that golden period when all necessary data have been collected and all possible hypotheses have been constructed and tested. The welfare of mankind, or the economic exploitation of the tundra ecosystem, call it what you will, cannot await the extreme demands of the Ivory Tower. Man the scientist has made tremendous progress in learning to understand the very large, the universe, and the very small, the molecule, through application of telescope and microscope. We sadly need a mesoscope to facilitate our understanding of the physical, social, and political environment in which we live, with which we interact in an increasingly alarming manner, and upon which our very existence depends.

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Climate: A Critical Factor in the Tundra†

The harsh arctic climate and the tundra are intimately and intricately related. The tundra is the product of a natural balance which involves climate, soil, water, land forms, and forms of life. If any one of these factors is altered, a delicate balance can be upset, possibly with profound effects. Major climatic changes have occurred in the past and even today climatic interludes act as major ecological controls. Sound use of the arctic by man, therefore, demands a sound knowledge of climate from both economic and ecological viewpoints.

CLIMATE AND CURRENT ARCTIC PROBLEMS

Technological advance for northern exploration and development has outpaced our understanding of the precarious balance of nature in the tundra, and it is this fact which gives rise to so much concern about the tundra. Since, however, development and operations within the arctic are in the national interest, meteorology must become involved in a major way not only for the advancement of science but to aid, through policy and planning, control and design, in ensuring that man's activities are rational.

The importance of understanding climate is self-evident since climate is a dynamic force which shapes the environment and influences almost every activity. The major need is not one of simply compiling a climatology, but rather one of fulfilling a host of subordinate, but very critical, basic roles such as understanding the problems of permafrost, ice, pollution, thermal degradation, ecology, and land-sea-air energy exchange. Development-oriented problems such as the extent, character, and move-

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ment of ice (which is effectively part of the tundra), hazards in off-shore drilling, in transportation, the siting of harbours, airports, and towns, are essentially climatic problems as well as problems in engineering.

Not only the present climate but also the forces and the effect of change, both natural and induced, must be clearly understood in a quantitative manner. These forces may emanate not only from within the arctic itself but also from other parts of the globe since neither the atmosphere nor the waters of the arctic are isolated. Local increases in population will cause changes; indeed significant increases are now evident in Alaska, whose population already exceeds 270,000 and is expected to double by the year 2000. The administration of people and natural resources, the assertion of sovereignty, the demand for leisure and wealth, and the search for knowledge in the north will continue to augment the impact of man on the arctic.

Required, therefore, is an understanding of the base-line micro- and meso-climates which now make possible the existence of arctic flora and fauna and also an understanding of how and in what degree man and nature may upset these micro-climates. Perhaps more vital is the understanding of the effects of broad-scale changes which may alter the general climate as well as microclimates over vast areas. Had the unruly Drake Point gas well been an oil well, what pollution could this have caused in the polar basin? And what would have been the effect of a blackened polar basin on the tundra climate, and the climate of the boreal regions? Moreover, great changes have occurred and can occur without man's intervention. Knowledge of energy exchange between the atmosphere, tundra, and arctic ice and water masses is, therefore, basic to reaching a rational arctic policy.

THE IMPACT OF CLIMATE

Extreme cold, driving winds, and blowing snow have challenged man's survival in the arctic and still pose major problems in exploration, development, and operations. They pose a continual threat to wildlife and plants as well. For example, wildlife populations may be drastically reduced by an unfavourable combination of climatic factors. Formozov (1946) describes extensive freezing-out of small rodents when snow cover was sparse and low temperatures in the habitats made it difficult to obtain food. A delay in spring snow-melt may deprive birds of suitable nesting sites, with the resultant loss of a year's hatch; and spring blizzards are responsible for major losses of caribou calves. The frequency of exposure to hazards makes the survival of many arctic animals appear fortuitous.

Temperature is an important ecological factor since it is generally the major one controlling the growth and development of plants. It is also

highly correlated with the state of ice-fields and permafrost and the activity of wildlife. The absence of trees, the shallow soil profile, the low rate of organic decay, the existence of ice-fields, and the rate of biological activity in general all are related directly or indirectly to air temperature. The tundra growing season is restricted generally to about three summer months. Over this period the mean air temperature is usually in the 0° to 10° C range and consequently growth processes are slow. Most arctic plants are low and creeping and for this reason the micro-climate near the ground and the study of temperature within this zone are of greatest importance, to understand not only growth but also permafrost and its degradation. Wasting of the permafrost in summer and temperature-induced snow-melt may also lead to erosion of slopes within areas of high ice content.

Extremes of temperature, particularly in combination with high wind and humidity or lack of snow cover, are often major biological controls, as well as parameters of interest in engineering design. In general small animals and plants avoid temperature extremes in winter by taking refuge within the snow cover; however large animals are not so fortunate. A thin or delayed snow cover and very cold air temperatures can be lethal to small mammals. Extreme low air temperatures of —50° C have been measured in most areas, and temperatures have remained below —35° C for periods of up to 20 days at several locations. Such measurements are taken in the air several feet above the ground surface, which may be 10 degrees or so colder.

The importance of snow cover cannot be overstressed. Because of its physical properties, especially its low thermal conductivity, snow cover provides excellent protection for plants and animals from winds and extremes of temperature. For many animals the snow is a medium in which they may tunnel and build nests; it is also a source of water. The quality of the snow also regulates the mobility of animals and their ability to forage and therefore is a major factor in migration as well as survival. Kelsall (1968) comments that "The most devastating occurrence would be the formation of a snow crust so strong and so lasting that it would prevent caribou from digging for lichens." The depth of snow is a critical factor in maintaining permafrost (at least 40 centimetres is required).

Sparse precipitation and permafrost resulting from the extreme, persistent cold pose major problems in obtaining adequate potable water supplies, in operating sewage systems, and in construction. Nevertheless, water excesses occur with snow-melt and occasionally with rain. Because of permafrost and a saturated active layer, summer rains are converted mainly to run-off or surface detention if the land is flat. Thus, when a rainstorm of less than one inch occurred at Resolute in 1960, "almost immediately numerous cataracts plunged down the hills to the east,

ditches overflowed, ... and the creek became a swollen torrent" (Thomas and Thompson 1962). In general, the annual precipitation averages about 200 millimetres, but this value is greatly exceeded on the windward flanks of coastal mountains. Studies at Barrow in Alaska indicate that precipitation there equals or only slightly exceeds evapotranspiration during the summer period (Britton 1957). This is probably true over most wet-land tundra. The high reflectivity of the snow surfaces results in low evaporative loss from most of the tundra over the greater part of the year; low temperatures, the lack of vascular plants, and energy exchange with the permafrost tend to keep evaporation low in summer.

Storms are most severe in coastal areas where recurrent gales make it necessary to find sheltered locations for harbours and townsites. For example, at Alert winds have exceeded 100 mph on many occasions, and in 1969 a three-day blizzard destroyed buildings and cut vital power supplies. On 24 December 1969, winds at Resolution Island were 110 mph, with the temperature zero; by Christmas morning the winds had subsided to 70 mph, with the temperature —2° F. Strong winds severely restricted oil drilling operations in Hudson Bay in 1969, causing waves estimated as high as 47 feet. At Port Burwell in 1965 early morning winds "blew away four buildings in forty minutes and heavily damaged the settlement's nets and boats ... the following November a 100-mile-an-hour wind tore the roof off a new warehouse and blew the seal shack to pieces ... the ice rafted in and piled up from 12 feet to 20 feet thick on top of the seal net" (Burgess 1967). Most townsites have been located to take full advantage of natural shelter from these tempests. Inland conditions are less severe, but natural shelter is still difficult to find.

Transportation, a major factor in most arctic activities, is particularly vulnerable to inclement weather. Despite the fact that blowing snow and blizzards may bring all transportation to a halt over extended periods, winter is the favoured season for travel since the land and sea ice are then firm underfoot. Exhaust from aircraft or other sources may readily produce persistent ice fogs in winter, and the arctic "whiteout" poses yet another problem for the traveller. With melting of snow and the "active-layer" in summer, much of the tundra is transformed into a morass which inhibits ground travel and often disables airports. Sea-ice limits marine navigation mainly to the late summer months, and travel in ice-fields during severe storms can be extremely dangerous.

Nature has successfully adjusted to the arctic environment, but most plants and animals exist precariously, mainly by taking refuge in a particular microclimate. The yield of the short growing period is inadequate to offset quickly the damage from grazing and mechanical traffic, and direct exposure of plants to the sustained winter cold threatens survival. The microclimates are in delicate balance and can be upset critically. For example, the alteration of the ground surface through vegetative modifica-

tion may result in a change of ground temperature with subsequent degradation of the permafrost. The removal of tall vegetation will result in an increase in wind speed near the ground, which in turn will cause a shallower, denser snow cover and a significant alteration of the thermal regime near and within the ground.

Natural variations in climate may also critically upset the habitat of both plants and animals and cause serious socio-economic problems. For example, a winter drought may deprive the flora and fauna of a protective snow cover (about 50 to 60 centimetres are needed for most tundra plants). An unseasonal melt may have a similar effect or produce damaging dampness within the snow cover. On the other hand, blizzards or heavy snows may be equally destructive to large mammals. Kelsall (1968) has shown that spring blizzards are a major factor in caribou calf mortality. The number of deaths increases directly with increasing wind-chill, depth of snow, etc., or as a result of the behaviour of caribou under blizzard conditions. Adult caribou may be acclimatized to severe weather events, but the thermoregulatory systems of the young will not compensate for prolonged exposure to low temperatures and strong winds, such as the convective cooling produced when temperatures are below 0° c and winds reach 12 metres per second. The calves may also become stuck in deep snow, be unable to stand on ice during strong winds, or be unable to keep up with the herd and obtain herd protection during blizzards.

Vibe (1969) found that periods of heavy snow have periodically destroyed animal populations of large sectors of Greenland: "In cold and dry winters food is easily accessible, and a great number of animals survive ... In warm and snowy winters the animals are exposed to lack of food and, consequently, starvation and only a few survive." Grazing animals will not feed when the depth of the snow cover is in excess of 50 to 80 centimetres, or a strong, durable crust forms on the snow, or the relative density of the snow exceeds 0.50. The average late winter snow cover on the tundra is 40 centimetres; fortunately the cover is heterogeneous because of wind action which exposes food for caribou and creates drifts which provide an acceptable habitat for plants and small mammals. The pronounced population cycles of 66 years for reindeer and similar cycles for lynx as well as shorter-period fluctuations may be at least partly explained in this manner.

CLIMATIC CHANGE

Climatic interludes or extremes which can occur within our lifetime effect a major control on the movement of plant and animal populations and may have far more profound effects on an ecosystem than the local

modification induced by human activity. The period from 1890 to 1940, for example, was one of general warming in the arctic in which the ice cover was substantially reduced in extent and thickness. This change was associated with increased zonal winds, a northerly cyclonic track, and a fortified Gulf Stream (Lamb 1966). During this period of warmer climate, in the Soviet Union agriculture advanced steadily northward to the arctic coast. Tikhomirov (1963) stated that in the Kola Peninsula "over the past three or four decades the number of adventive weeds has reached 142, and 57 species have invaded fields from the aborigenous flora."

The reappearance of arctic drift ice off the north coast of Iceland after an absence of 45 years has made the socio-economic importance of periodic fluctuations in climate quite clear. Thousands of Icelanders emigrated during the preceding cold spell, 1870–1918. A 1 deg c drop in temperature means a 15 per cent reduction in crop yields, and can result in a migration of herring from Icelandic waters, as has occurred previously when colder water surrounded the island. The incipient cold interlude therefore poses a major economic problem for the island, which is very dependent on open seas and harbours (Kristjansson 1969).

Large-scale climatic change has occurred within the past 2,000 years. It can occur again; and it may happen rapidly. The impact of such a change may vastly outweigh that of many of the small-scale changes which sometimes concern us. The change may occur naturally, or be induced artificially by activities inside or outside the tundra area.

Bryson observed fossil soils in Keewatin territory which contained relics of spruce trees and evidence of a forest fire. The burned area had subsequently been covered by sand dunes. Larsen and Bryson have placed the forest epoch at some 2,000 years ago (Larsen 1967; Bryson, public lecture, University of Toronto, Feb. 1970).

Man's activities can also induce change. The decrease in solar radiation, particularly near large industrial centres, is one achievement. But pollution is not just a local affair. Robinson and Robbins (1969) observed air arriving over the Greenland icecap from the American industrial area with a carbon monoxide content five times greater than that arriving from other trajectories. The amount of aeolian dust is increasing because of land use practices and industry. Dusty air is heated by absorbed solar radiation and also suppresses long-wave radiation loss from broad expanses of the earth's surface (Davitaya 1969).

Studying the cooling trend in the Northern Hemisphere, which since 1940 has seen a marked increase in quantity of pack-ice, Budyko (1969) found a corresponding 4 per cent reduction in solar radiation (1 deg c per 1 per cent reduction), possibly due to manmade dust. Periods of volcanic action in the past are credited with causing similar, but more

precipitous cooling. Budyko's comments resulting from his schematic-model analyses indicate that:

1. There is a possibility that an ice-free regime will exist in the polar basin in our unstable glacial epoch.
2. Glacier expansion could evolve to a critical latitude after which complete glaciation of the earth could occur, i.e. there could be a climatic catastrophe.
3. Man is increasingly heating the atmosphere and within 200 years will be producing amounts of heat which are comparable to that received from the sun; this energy could offset the effects of reduced solar radiation and result in melting of polar ice.

Most striking are the indications that slight changes in the energy balance resulting from activities outside the tundra may effect major changes on the tundra as well as other areas of the globe, and that the direction of these changes is uncertain.

Major change is obviously a climate force to be reckoned with in evaluating the impact of climate. Changes which may destroy permafrost and create seas and forests, or cause similar large-scale vegetative or landform alteration, can result naturally or by the combined effects of mankind. Extensive research into the atmosphere-ice-ocean complex is needed before we shall be able to understand and adequately predict natural changes and those effected by man.

SUMMARY AND CONCLUSIONS

The critical nature of the climate-ecology relationship and climate-development relationship cannot be overstressed. The harsh, cold arctic climate has been a fundamental force in shaping the tundra, and the nature of the tundra can be easily upset by slight climatic changes. A knowledge of climate, particularly the critical extremes, is therefore basic to the understanding of tundra ecology and the prudent conquest of the arctic by man.

The flora and fauna of the tundra have adjusted to a climatic regime of fairly short duration but exist mainly by taking refuge within certain microclimatic zones. They may be destroyed or induced to advance outside the normal habitat by climatic interludes or extremes. This natural control should be taken into consideration in arctic policy and planning.

In high latitudes records available for planning are sparse, short-term, and biased. Long-duration records are essential in the assessment of climatic change and design. Also more numerous records are essential for the interpretation and transposition of research results from other disciplines. Development of an adequate measurement network is therefore a necessity.

In addition to short-duration variability of climate, the possibility of major, longer-term climatic change must be considered. Major changes have occurred naturally within the not too distant past, and the forces exerted by man's influence now appear to be sufficient to match natural forces which can produce major climatic change. These forces may result from development outside the tundra area, as well as by man's design or accident within the tundra. Our science is not yet adequately advanced to comprehend the nature of the risks fully.

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